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ANALYSIS OF SUPERCONDUCTING ELECTRIC MACHINES FOR NAVAL SHIP PROPULSION.

Lawrence George St. John

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ANALYSIS OF SUPERCONDUCTING ELECTRIC MACHINES FOR NAVAL SHIP PROPULSION

by

LAWRENCE GEORGE ST JOHN

BSEE, PURDUE UNIVERSITY
(1972)

SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

OCEAN ENGINEER

AND THE DEGREE OF

MASTER OF SCIENCE

IN

SHIPPING AND SHIPBUILDING MANAGEMENT

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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ANALYSIS OF SUPERCONDUCTING ELECTRIC MACHINES FOR NAVAL SHIP PROPULSION

by

LAWRENCE GEORGE ST JOHN

Submitted to the Department of Ocean Engineering on May 12, 1978 in partial fulfillment of the requirements for the degreee of Ocean Engineer and the degreee of Master of Science in Shipping and Shipbuilding Management.

ABSTRACT

A proposed ship propulsion system which incorporates superconducting electric machines as the transmission system between the prime mover and the propeller is described. The propulsion system employs gas turbine prime movers, synchronous generators and synchronous motors with superconducting field windings, switch gear with a cycloconverter, variable frequency, power controller between the generators and the motors. The proposed system in the DD963 destroyer, which has a gas turbine propulsion system driving controllable pitch propellers through reduction gears. The resulting ship is compared with the original on the basis of weight and volume. A smaller ship with an identical payload but a smaller propulsion system is constructed to take advantage of the weight and volume savings which are a result of using superconducting electric machinery. The smaller ship is compared with the original DD963 on the basis of weight, volume, effeciency and cost ceiling for the superconducting electric propulsion system.

The proposed superconducting motors and generators are modeled mathematically and simulated on a digital computer. Components for the motors and generators are designed to determine their individual characteristics and their interactions with other elements of the machines. The design analysis of the superconducting machines indicates they will be very small and lightweight.

Final comparison of the proposed and existing ships shows a 14% reduction in ship displacement, a 9% reduction in total volume, a 17% reduction in fuel carried and a propulsion system that is 50% lighter and requires 33% less volume.

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Title: Associate Professor of Electrical Engineering

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Title: Associate Professor of Marine Systems

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NAVAL ARCHITECTURE DEFINITIONS

SYMBOL	UNITS	DEFINITION
I. Gross Characteristics		
Δ	(tons)	Fuel Load Displacement
∇	(ft^3)	Total internal volume
L or LBP	(ft)	Length of hull at waterline
B	(ft)	Beam(width) of hull
D_{AVG}	(ft)	Average depth or average height of main deck
T	(ft)	Draft of hull
VCG	(ft)	Vertical Center of Gravity of ship
C_p		Prismatic coefficient. The percentage of a prism, which is the same L,B,T as the underwater hull, actually filled by the underwater hull. For a Box of L,B,and T units, $C_p = 1$.
C_x		Midship section coefficient. The percentage of a rectangle, which is the same B and T as the underwater hull, actually filled by the midship hull cross section. For a rectangle $C_x = 1$.
GM/B		Measure of ship stability (Resistance to rolling)
V_s	(knots)	Maximum sustained speed
$R@V_e$	(Naut.Mi.@Kts)	Range at cruising speed
SHP	(hp)	Main propulsion horsepower rating
SFC	(lbs/hp-hr)	Specific fuel consumption in pounds per horsepower-hour
M	(M)	Total manning complement

SYMBOL	UNITS	DEFINITION
II. Weight Fractions*		
WTGP1/Δ		Structural weight fraction
W_{MB}/Δ		Machinery Box weight fraction
WTGP2/Δ		Propulsion system weight fraction
W_{OPS}/Δ		Ships operations weight fraction
W_{PERS}/Δ		Personnel weight fraction
W_{PAY}/Δ		Payload weight fraction
III. Volume Fractions		
VOL MB/∇		Machinery Box volume fraction
VOL OPS/∇		Ships operations volume fraction
VOL PERS/∇		Personnel volume fraction
VOL PAY/∇		Payload volume fraction

* weight and volume fractions are non-dimensional

IV. Specific Ratios		
WTGP2/SHP	(lbs/SHP)	Propulsion system specific weight
VOL MB/SHP	(ft^3/SHP)	Machinery Box specific volume
VOL HAB/M	(ft^3/MAN)	Personnel specific volume
V. Densities		
DISPLACEMENT/VOLUME	(lbs/ft^3)	Total ship density

VI. BSCI Weight Groups *

BSCI weight groups are a breakdown of ship weights by ship systems as listed below:

WTGP1	(tons)	Hull Structure

SYMBOL	UNITS	DEFINITION
WTGP2	(tons)	Propulsion System
WTGP3	(tons)	Electric Plant
WTGP4	(tons)	Communication and Control
WTGP5	(tons)	Auxiliary Systems
WTGP6	(tons)	Outfit and Furnishings
WTGP7	(tons)	Armament
WTGP8	(tons)	Loads

* Complete listing of the contents of each weight group are contained in Appendix I.

INTRODUCTION

Superconducting electrical machines can now be considered "state-of-the-art" for marine applications. This paper investigates the impact of converting a DD963 gas turbine driven propulsion plant from mechanical power transmission to superconducting electrical power transmission. The DD963 is a 7885 ton, twin screw, 30+ knot destroyer with a 6000 mile endurance range. The propulsion plant prime movers are four 20,000 horsepower gas turbines. The mechanical drive propulsion system of the DD963 requires two gas turbines driving the reduction gear for each shaft. The physical connection of a gas turbine to a reduction gear limits a gas turbine to driving that one shaft only. In a electric drive propulsion system any one gas turbine can drive either or both shafts at the same time. At the cruising speed of 20 knots, the mechanical system required two gas turbines (one for each shaft) to be in operation. At this low power level, each turbine is operating in a very uneconomical off-optimum fuel consumption performance mode. A single gas turbine providing the power for a 20 knot cruising speed and using electric drive to transmit this power to both shafts, operates at a more economical performance power level. For this reason, an electric

drive requires much less fuel than the mechanical drive system. The criteria for comparing the electric drive ship to the original mechanical drive DD963 is the ships must perform the same military mission without changing the speed and endurance characteristics.

Figure 1 contains a major weight breakdown for the DD963 baseline ship, a four gas turbine electric drive ship, and a three gas turbine electric drive ship. When a straight conversion of the four gas turbine driven DD963 to electric drive is made a propulsion plant weight and fuel weight savings of 485.1 tons is realized. Since the DD963 is a weight limited ship (no weight margin to spare), this is a dramatic improvement in the overall ship characteristic.

The DD963 was originally designed with a large excess margin of volume, which is now even greater with the 485 ton reduction in displacement. The next logical step was to take full advantage of the propulsion plant and fuel weight reductions and reduce the overall size of the ship. This further reduced the fuel weight; less fuel required to drive a smaller lighter weight ship. A smaller and lighter ship also requires less installed horsepower, which permitted the reduction of the propulsion plant to three 20,000 horsepower gas turbines. An overall savings due to hull, propulsion plant and fuel

weight reductions in a three gas turbined powered ship is 1084 tons for a 14% weight reduction over the baseline ship.

The three-engined ship has the same mission performance capabilities as the larger four-engined ship. The only differences between the two ships is the three-engined ship is cheaper to build, maintain and operate.

	DD963 BASELINE	4 ENGINED ELECTRIC DRIVE	3 ENGINED ELECTRIC DRIVE
Hull Structure	3137.1	3105.6	2757.7
Propulsion	789.2	504.1	401.2
Electric Plant	296.8	296.8	275.9
Command & Control	250.3	250.3	250.3
Auxiliary Systems	739.8	739.8	735.5
Outfit & Furnishings	454.3	454.3	445.9
Armament	159.2	159.2	159.2
Margin	100	100	100
Fuel	1606	1404	1334
Loads	353	353	341
Full Load Displacement	7885	7366.4	6800.7
% Weight Saving from Baseline	0	6%	14%

MAJOR WEIGHT BREAKDOWN
FOR THE DD963 BASELINE SHIP
AND TWO ALTERNATIVE ELECTRIC DRIVE SHIPS

Figure 1

In comparison to other propulsion systems, the superconduction electric machinery offers a truly compatable transmission system with which to take advantage of the high-speed, compact and highly maintainable gas turbine, without the use of gears or controllable reversible pitch propellers for reversing. The arrangement flexibility inherent to electrical propulsion systems can now be realized without the weight penalty associated with conventional electrical machines. The cost of installing superconducting machines onboard a ship appears to be feasible when compared to the potential benefits associated with this use.

CHAPTER 1

ELECTRICAL MACHINERY FOR SHIP PROPULSION

1.1 Background

Interest in electrical propulsion systems has been generated by their inherent ability to provide speed reduction between a high-speed, efficient, lightweight prime mover and a much slower, efficient propeller. The primary advantages of such an installation is the flexibility of design and arrangement of the machinery plant and the flexibility of control.

While electrical transmission systems have a number of advantages, the primary reasons for a lack of widespread use have been:

Higher acquisition cost than mechanical drive alternatives.

Greater weight and volume requirements than mechanical drives.

Higher transmission losses overall, resulting in a lower total system efficiency and a higher fuel usage than mechanical drives.

With the development of superconducting electrical machinery for shipboard use, a great savings in weight, cost and volume may now be obtainable. Superconducting machinery provides all of the advantages of electrical propulsion with the disadvantages of large weight and

volume being greatly reduced. The reductions in size and volume can have a dramatic effect upon the ship design by eliminating the need for the large machinery box required by the current mechanical drive propulsion systems. The result will be an increase in available volume in a highly desirable location, which can then be used for other shipboard functions. Another alternative result of a volume and weight saving propulsion system may be a smaller and less expensive ship that performs the same missions as the larger volume ship with a mechanical drive system.

In the case where the power plant requires the use of several prime movers, the electric drive provides an efficient method of coupling these units to the propeller without the use of mechanical clutches or couplings. The electric drive system can be arranged in such a manner that the ship operating at less than full power will require only a minimum number of prime movers to be in service. (Chapter 2 contains the propulsion plant operating characteristics.) This contributes to greater fuel economy and provides down time for routine maintenance on idle propulsion units.

Since some prime movers, such as gas turbines, are unidirectional machines; an electric drive can produce the required reverse rotation of the propeller by relatively

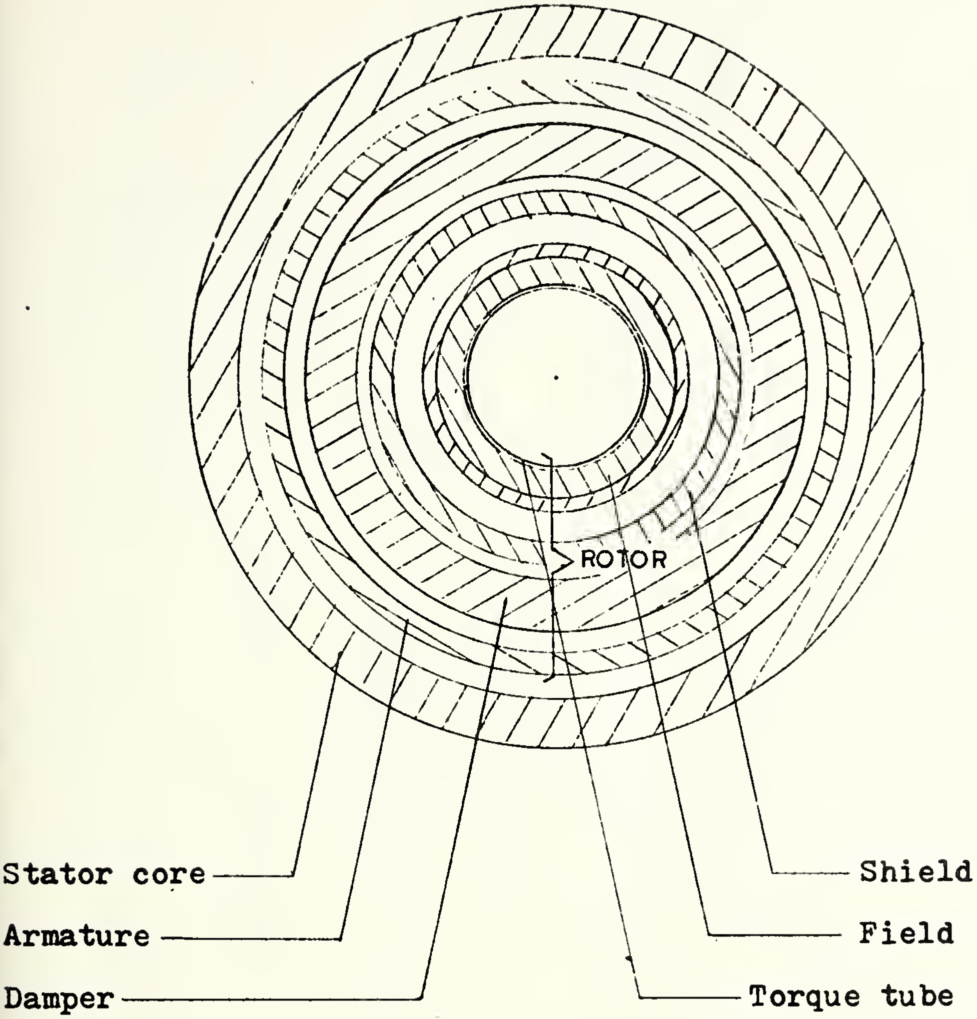
simple controls. This eliminates the requirement of the unidirectional prime movers for controllable and reversable-pitch propellers (CRP) to provide the desired reverse rotation. Switching to fixed-pitch propellers eliminates several disadvantages of the CRP: the extensive hydraulic control system, the maximum upper loading limit of a single propeller to 40,000 shaft horsepower, and the reduced effeciency of a CRP propeller over a fixed pitch propeller of the same given size and characteristics.

Electric propulsion systems are classified as either direct-current (dc) or alternating-current (ac). Electric systems can further be defined by the type of prime mover involved, such as diesel engines or gas turbines. Traditionally dc drives have been desirable because they provide more rapid and continuous control of the propeller speed for excellent maneuverablility. As a result, superconductors were first applied to dc machines, thus increasing the maximum practical power level while allowing for small, light weight machinery. Superconducting dc machines require that full electric power must be carried onto the rotor at high current and low voltage. This presents significant current collection problems in high-power machines and constitutes a distinct disadvantage.(1)(2)(3)

The high-power electrical connections for an ac

machine can be made directly to a stationary armature winding. They are of high voltage and low current when compared to a dc machine and are not subject to the high current collection problems of the dc machine. However, a high-power ac machine will require a rotating superconducting field winding of low current and voltage. High-power ac synchronous machines have been proven practical by experimentation at MIT(2)(3)(4) and elsewhere. A great deal of work has also gone into proving that ac machines are suited for shipboard use.(5)(6)(7)(8)

The superconducting synchronous motor and generator under investigation in this paper belongs to the class of machines referred to as cold shield superconducting machines.(see Fig. 1.2) The principal functions of the cold shield (referred to as cryogenic shield or shield) are to shield the superconducting field winding from alternating magnetic fields and to prevent heat transfer in the form of thermal radiation.(2)(4) The rotor itself is held at or near $4.2^{o}K$ while the shield would operate at a temperature of about $20^{o}K$. The damper shield (called the damper) operates at approximately room temperature and serves as an electro-mechanical damper and as a shield for time-varying fields. In the event of a fault, the damper absorbs strong crushing and torque loads. These loads are so strong that the damper must be strong,



CROSS SECTION OF SUPERCONDUCTING MACHINE

Figure 1.1

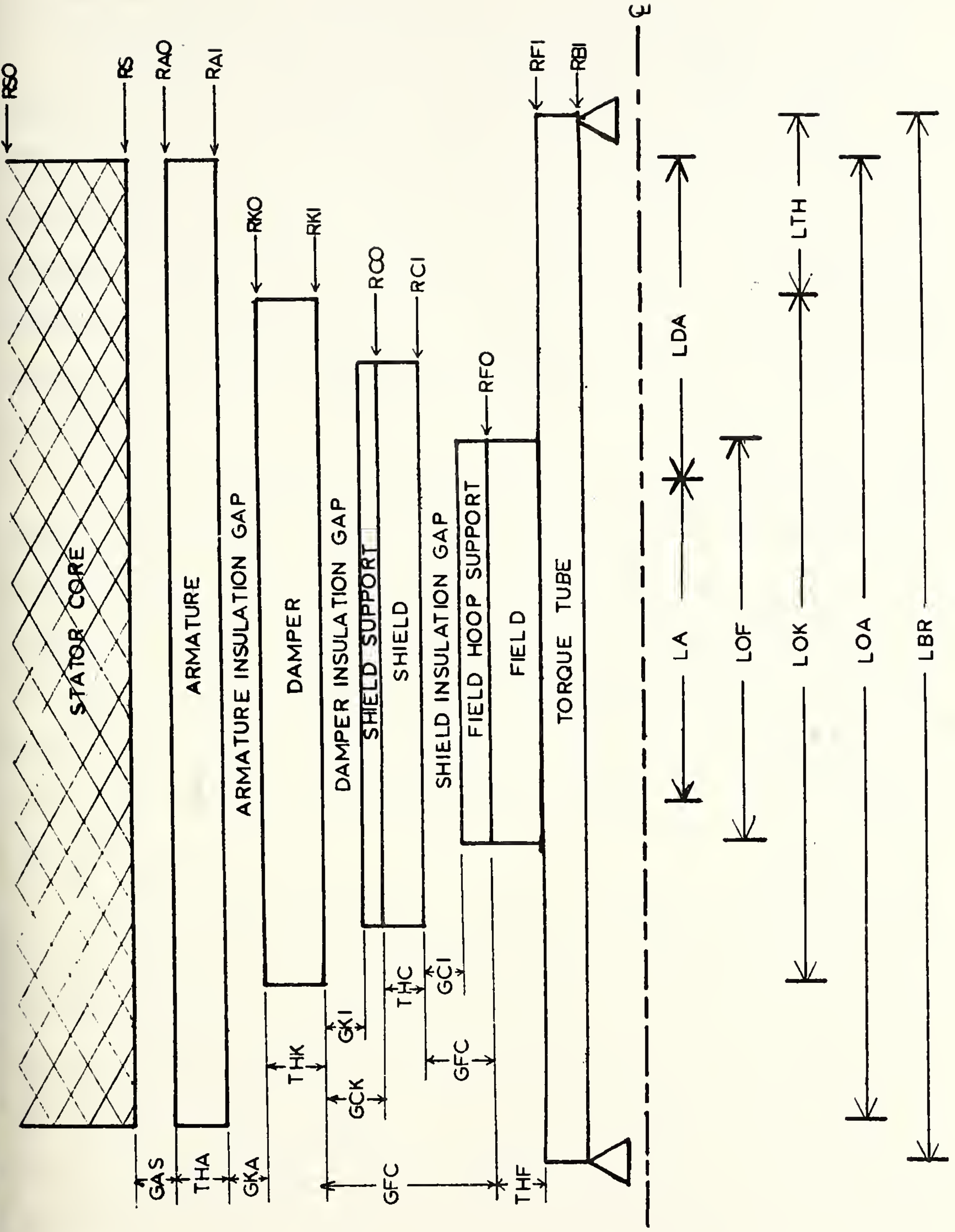


Figure 1.2

SUPERCONDUCTING MACHINE ELEMENTS

consequently thick, relative to the shield.(8)

The rotor cross section consists of eight elements. (see Fig. 1.1) Arranged from inside to outside, they are: torque tube, superconducting field winding, field hoop support, shield insulation gap, shield, shield support, damper insulation gap, and damper. Between the armature and the damper is a gap which holds a vacuum to reduce the rotor windage loss and to provide thermal insulation.

The outer shell outside the armature (called the stator core) provides a uniform boundary condition and confines the magnetic field to the machine. This shell is of laminated iron to reduce eddy current losses. The iron in this shield is soft and must be surrounded by an outer shell to protect it. This steel outer shell acts as a frame and serves as a structural support for the entire machine. Fig. 1.1

The torque tube is actually a cylinder that serves as a cryogenic thermal distance piece and supports the field winding. The torque tube must be thick enough to withstand the torque that is imparted to the cylinder by the magnetic flux field. The torque tube is sized for normal torque, based on the machine's full power rating. Stainless steel is used for the construction of the torque tube.

A superconducting field winding is the heart of the superconducting machine. This superconducting field produces an intense magnetic field without the use of: heavy and bulky ferrous material, electrical dissipation, and negligible electric power losses. When the temperature is reduced below a critical value (approximately 5^{o}K) the superconductors support very high currents without resistance losses. Current in the stationary armature winding interacts with the large flux wave generated by the field winding and pulls the rotor around at synchronous speed in the same manner as a conventional machine. A conventional electric motor or generator operating at room temperature requires a heavy iron core to produce the magnetic fields necessary for proper operation. At these temperatures, there is electrical dissipation and power losses. To overcome these losses, the machine must be made even larger. The size and weight of the iron core then controls the size of the conventional machine. Conventional machines become big and heavy when compared to superconducting machines of the same size. It is in this manner that a much smaller superconducting machine develops the same horsepower as a much larger conventional machine.(3)(5)(6)(7)(9)

1.2 Baseline Ship

A particular propulsion system cannot be judged

"as good as" or "better than" another propulsion system unless the systems are compared for a particular mission. For a Navy ship the primary mission of the propulsion system is to move a given pay load over a given distance at a required speed. Simple comparison of one propulsion system to another is not sufficient. The overall impact of each system on a given ship must be determined. Since, in most cases, the propulsion system has the largest single impact on the total ship, the propulsion plant becomes a major factor in final ship size, cost and pay load.(10) The sizeable volume and weight required for a propulsion plant and its fuel over shadows all other volume and weight requirements in a Navy ship. Not only is the magnitude large, but a feature unique to the propulsion system requires space which cannot be split up or scattered throughtout the ship, and in most cases it occupies the prime space in the ship.(11) For the above reasons, a ship with a conventional propulsion system was needed for propulsion system comparison. Such a baseline ship was found in the DD963 class ship. The selection was based on the following primary consideration: The best lightweight prime movers for the superconducting system are gas turbines;therefore, the baseline ship should be gas turbine powered.

The selection of the DD963 as the baseline ship was

governed by the fact that it is the only totally gas turbine powered ship in the U.S. Navy about which a good deal of specifications and information has been published. The basic characteristics of the DD963 are contained in Table 1.1.(12)(13) The power plant weights by BSCI subgroups are shown in Table 1.2.(12) The discrepancy between weight group 2 in Table 1.1 and the propulsions plant total weight in Table 1.2 can probably be attributed to two different authors assigning individual auxiliary equipment weights to different weight groups.

For a comparison of propulsion systems to be based on a computer synthesis model, the volume and weight associated with the remaining ship functions must be held constant. The items to be held constant are BSCI weight groups 3,4,5,6 and 7. (see Table 1.1 for definition of BSCI weight groups). The full load loads will be allowed to change only to the extent required by changes in fuel dictated by the respective power plants. Weight group 1 will change by the amount required to compensate for different propulsion plant sizes and the different fuel requirements associated with each propulsion plant. With the above criteria being observed throughout the computer simulations, the resultant weight and volume changes will be due only to propulsion plant changes. The selection of the "best"

Length	529 ft. water line, 563.3 ft. overall
Beam	55 ft.
Draft	29 ft. (navigational) 19 ft. (hull)
Speed	30^+ knots
Displacement	Approximately 7800 Long Tons (fully loaded)
Crew	Approximately 18 officers 232 enlisted men
Propulsion	4 LM2500 Gas turbine engines 80,000 shp 2 shafts, 2 Controllable Pitch Propellers
Electrical Power	3 Gas turbine driven generators
Armament	2-5", 54 caliber guns 1 ASROC 8 Tube Launcher 2 ASW Torpedo Mounts-Triple barrel
Sensors	Fire Control, Surface Search and Air Search Radars, Long Range Sonar

BSCI GROUP	DESCRIPTION	WT(LONG TONS)
1	Hull Structure	3105.54
2	Propulsion	759.93
3	Electric Plant	293.81
4	Communications & Control	354.17
5	Auxiliary Systems	722.98
6	Outfit & Furnishings	452.01
7	Armament	152.16
	Light Ship (W/O Margin)	5829.61
	Margin	89.87
	Light Ship (with Margin)	5919.48
	Full Load Loads	1865.66
	Full Load Displacement	7785.14

Table 1.1

BSCI NO.	SUBGROUP DESCRIPTION	WT(LONG TONS)
201	Propulsion Units	244.14
203	Shafting, Bearings & Propellers	253.15
204	Combustion Air Supply Systems	58.34
205	Uptakes(Smoke pipes)	130.51
206	Propulsion Control Equip.	10.97
210	Fuel Oil Service System	10.10
211	Lubricating Oil System	31.24
250	Propulsion Repair Parts	8.50
251	Propulsion Operating Fluids	42.23
	Total	789.18

Dry Weights of Principal Propulsion Components

COMPONENTS	NO.PER SHIP	WT(LONG TONS)
Propulsion Gas Turbines	4	81.25
Propulsion Reduction Gears,Inc.Acc.*	2	149.56
Propulsion Bed Plates	2	53.58
Shafting	*N/A(Total)	156.43(34 ton/ft)
CRP Propellers	* 2	46.88
CRP Propeller Hyd.Oil Power Module	* 2	5.45
CRP Propeller Oil Dist. Box	* 2	2.32
Line Shaft Bearings	* 5	9.72
Prop.GT Enclosure Cooling Fans	4	2.32
IR Suppression Booster Pumps	2	1.61
FO Service Booster Pumps	4	1.25
LO Service Pumps	4	4.46
Prop GT Lube Oil Storage & Conditioning Assembly	4	2.95
Prop GT Free Standing Electronics Enclosures	2	.38
Total		516.16

*Removed or replaced for electric propulsion

Table 1.2

propulsion plant can be based between two ships identical in mission performance with differences only in propulsion plant size, weight and operating charcteristics.

With this data as input, a ship synthesis model computer program(14) was used to simulate each of the different propulsion systems and resultant ship. A sample output of this computer program is shown in Appendix H.

It soon became evident that the DD963 would not fit directly into the ship synthesis model without some "bias" being fed into the computer program. The synthesis model is based on all past design practices and limitations; the DD963 is based upon a present and new design philosophy.(15)

The DD963 is a very spacious and roomy ship by any design standards. When the DD963 specifications were fed into the computer model, it generated a ship 900 long tons lighter than and 100,000 cubic feet of internal volume smaller than the actual DD963. This is due primarily to the DD963 being a weight limited ship with excess volume available for all shipboard functions. The "bias" had to be fed into the computer program to include this excess volume in the simulated ships.

During the comparison of the electric propulsion system to the mechanical propulsion system, care had to

be taken not to lose this excess volume when the electric propulsion was inserted into the program. Loss of this excess volume would give a false indication of the desirablility of the electric propulsion systme due to a much smaller volume requirement for propulsion machinery.

As a check to ensure that none of this excess volume was lost or misplaced by the computer program, the decision was made to make two comparisons of the electric propulsion system and the mechanical propulsion system. This will indicate if a volume saving is due to the electric propulsion system or if it is due to the tightening up of a loose design.

The first comparison is to be made between DD963s with the excess volume as simulated in the computer with bias included in the program. The second comparison is to be made between DD963s as simulated on the computer based on past design limits where no excess volume is to be found. If the same relative volume and weight changes are observed in both comparisons, it would be a good indication that resultant weight and volume savings,(as simulated in the computer), of the electric propulsion system based on the actual DD963 would indeed be a realized saving and not a false indication of volume reduction. The DD963 is limited in weight,with any weight decrease bringing about an improvement in overall ship characteristics.

The big advantage in the electric propulsion system is the weight savings due to decreased fuel and propulsion plant weight. The actual results of these comparisons can be found in Chapter 5, with sample computer outputs given in Appendix H and E.

CHAPTER 2

PROPULSION MACHINERY DESCRIPTION

2.1 Machinery Characteristics

Once the prime mover and the transmission system have been selected the next design step is the selection of the basic propulsion plant configuration. At this point, the physical location of the individual pieces of equipment within the ship is not critical. The importance lies in how the power is to be passed from one unit to another to end up at the propeller with the least power

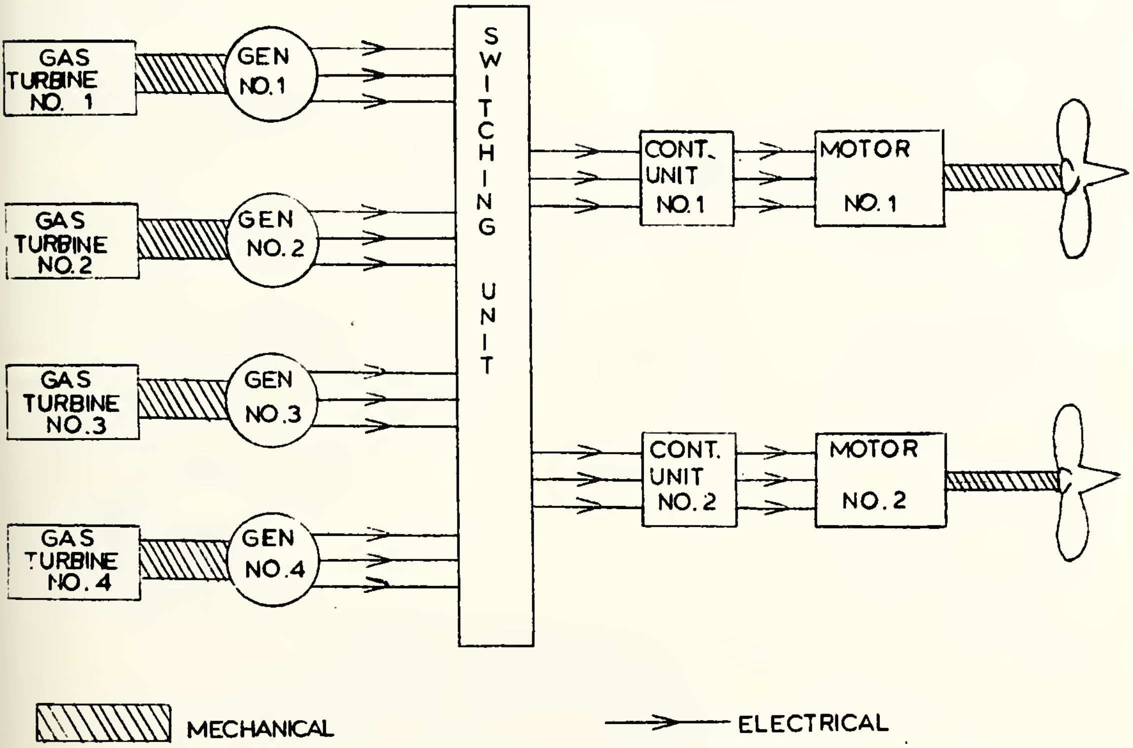


Figure 2.1

loss. A straight conversion of the DD963 power plant to electric propulsion is shown in Fig. 2.1.

The four gas turbines are "of type" LM-2500 configured in an enclosed module for marine installation. The enclosed module provides engine cooling, sound attenuation, internal lighting, view windows, and fire extinguishing capability. Output power is via two flexible couplings connected directly to the input shaft of the superconducting generator. The characteristics of the gas turbine are given in Table 2.1. The performance characteristics are shown in Fig. 2.2 and 2.3.

Rating Conditions		
Inlet Air Temperature	(Power rating)	100°F
Inlet Air Temperature	(SFC rating)	80°F
Maximum Power Rating		
Brake Horsepower		21.500 HP
Power Turbine Speed		3,600 RPM
Specific Fuel Consumption(SFC)Max		0.42 lb/hp-hr
Off Design Performance		see Fig.2.2
Dimension (Module)		
Length		26 ft. 6 in.
Width		9 ft. 0 in.
Height		9 ft. 6 in.

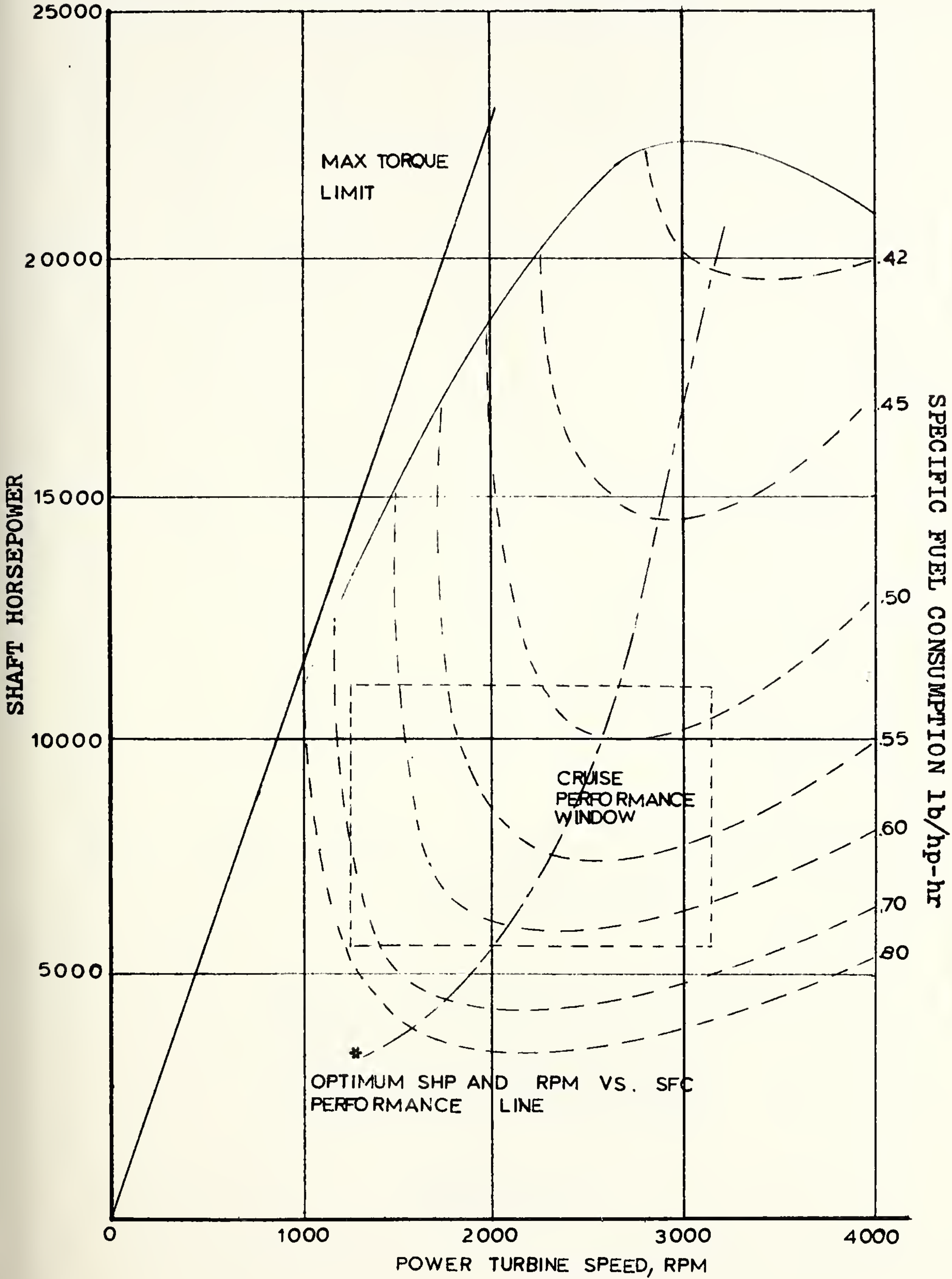
DD963 PROPULSION
TURBINE CHARACTERISTICS

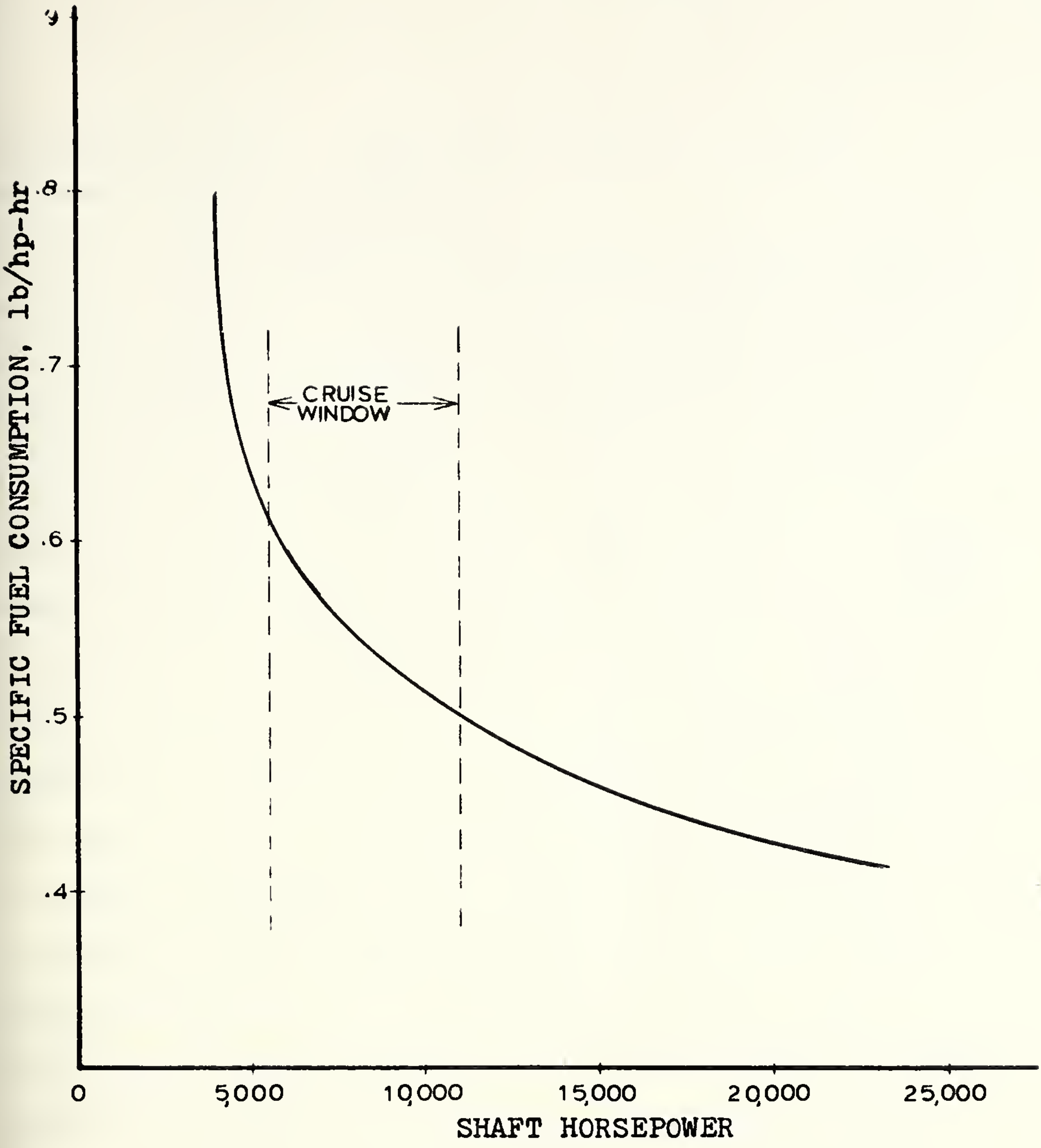
Table 2.1

The power out of each gas turbine is transmitted directly to a 20,000 HP superconducting generator. The operating characteristics and dimensions of the generator are shown in Chapter 4. The output frequency of the generator will be 60 HZ when the turbine is at 3600 RPM (full power), and 30 HZ when the turbine is at 1800 RPM (min. operating speed of power turbine), see Fig.2.3. At turbine speeds between 1800-3600 RPM, this frequency change will directly control the speed of the motor and hence the propeller speed.

The switching power control unit produces one of the big advantages of an electric propulsion system over a conventional mechanical system. In the mechanical system, any given gas turbine is physically connected to a specific propeller. In the electric system, any gas turbine-generator can be connected to either propeller. At low speeds, this can result in great fuel savings, as both propellers can be driven by one gas turbine. A single gas turbine operating at higher power is much more fuel economical than two turbines operating at a lower power rating. In Fig. 2.2, one turbine providing 17,000 HP has an SFC of .445 lb/hp-hr at 3000 RPM, while two turbines providing 17,000 HP(8,500 HP each) have an SFC of .56 lb/hp-hr at 2300 RPM. This works out to be a savings of 1955 lb/hr. This is only one example of savings offered by an electric

Figure 2.2-ESTIMATED MINIMUM PERFORMANCE





SPECIFIC FUEL CONSUMPTION OF THE LM-2500 GAS TURBINE ENGINE AS A FUNCTION OF POWER LEVEL AND OPTIMUM POWER TURBINE SPEED

Figure 2.3

propulsion system. A detailed breakdown of overall savings are given in Chapter 6.

The control unit performs several important functions. The most important is providing the necessary reversibility of the propeller by controlling the direction of rotation of the superconducting motor. In addition to controlling the direction of the motor, the control unit can also control the speed of the motor. Speed control is accomplished by controlling the frequency of the electrical power to the motor. A possible method of propeller control for propeller speeds of 85 to 170 RPMs, would be the control unit employing a fixed frequency reduction and the speed of the propeller being controlled directly by the speed of the gas turbine (1800-3600 RPM) and the electrical output of the generator (30 to 60 HZ). At propeller speeds of 30 to 85 RPMs, the control unit would control the speed of the motor by using a variable frequency reduction. For this range of propeller RPM, the gas turbine would be held at a constant speed with the generator delivering power at a constant frequency. In this example, the control unit controls both the speed and direction of the propeller. Examples of different control units have been proposed.(2)(3)(5)(7)

In basic design, there is no difference between a motor and a generator. Superconducting motors are

very similar to the superconducting generators. The major difference being, the motors are 40,000 HP each at 200 RPM maximum design speed, where the generators are only 20,000 HP each at 3600 RPM maximum design speed.

Last in propulsion is the propeller which delivers the output of the motor to the water. The controllable-reversible-pitch propeller presently on the DD963 can be replaced by fixed pitch propellers, which provides a higher effeciency. See Table 2.2.

	CRP	FIXED PITCH
Rated Power	40,000 HP	40,000 HP
Rating RPM	168 RPM	170 RPM
Effeciency(open water)	70%	73%
Diameter	17 ft.	17 ft.
No. of Blades	5	5
Hub Ratio	.30	.17
Expanded Area Ratio	.75	.75
Weight	23.4 L Tons	18 L Tons

PROPELLER CHARACTERISTICS

Table 2.2

The cryogenic refridgeration system is not shown in Fig. 2.1 , but it is an essential part of the propulsion system. The best configuration at present is to have one refridgeration system per electric motor, and at least

one system per two electric generators. With cross-connect piping installed, this will provide the required reliability without excessive redundancy in the cryogenic systems.

Chapter 3 contains the design of the superconducting motors and generators described in the above propulsion system. The remainder of the electrical transmission system is covered in Chapter 4.

CHAPTER 3

DESIGN OF SUPERCONDUCTING MACHINE

3.1 Introduction

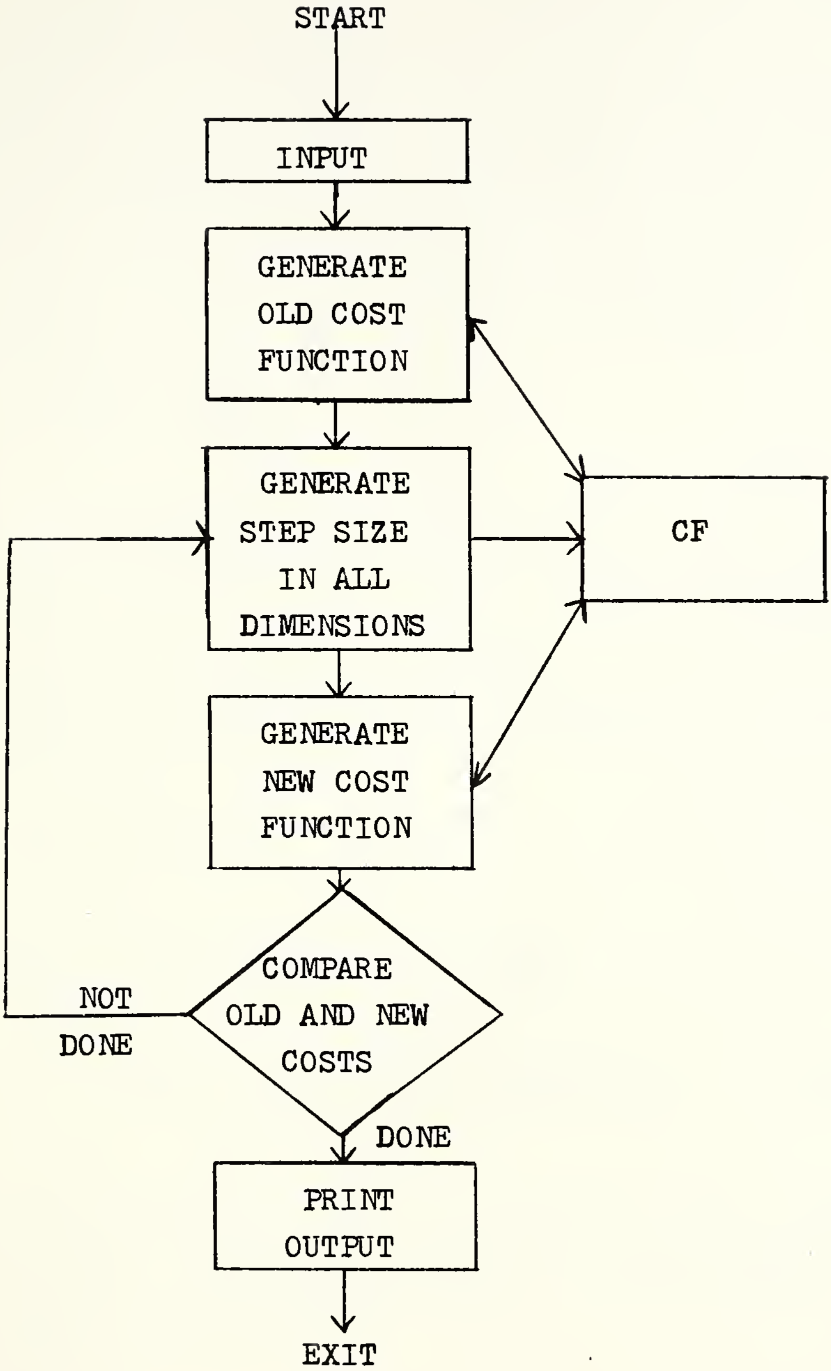
An optimization design program for the basic electrical design of superconducting generators and motors, has been used in this thesis, see Appendix A for computer program listing. This computer program optimizes the machine by seeking a design which minimizes a total "cost function", which is a function of machine weight, dimensions and operating characteristics. The operation of the optimization program and the bulk of the subroutine CF can be found in KIRTLEY et. al.(2)(4) The portion of the subroutine CF which computes the damper stress and thickness is from a thesis by Furuyama.(8) A detailed development of the mathematical equations and theory abstracted here, can be found in these previous works.

The function of the computer program is to select an optimum design of a superconducting generator or motor for a machine of a given physical configuration and horsepower rating. An initial set of dimensions is assumed for the machine. The computer program, using this initial guess as a starting point, attempts to design a machine that provides the required horsepower, with the least weight, smallest dimensions and least internal

power loss based on a set of rules.

The program is based on an optimization approach. For each trial design, a single number, called a "penalized cost" is generated. The program attempts to find a design for which this "penalized cost" function is a minimum. To accomplish this, it searches over the values of seven machine dimensions and the value of field current, see Table 3.1. The cost function is the product of two numbers:

1. The "cost" is the sum of material weights.
2. Penalty functions are established for several variables that will have values that are either acceptable or not acceptable. The penalty functions have very large values when their associated variables are unacceptable. The penalty functions are multiplied together and then multiplied by the "cost" to form the "penalized cost". Penalty functions exist for:
   - Maximum field current density
   - Shaft critical speed
   - Shaft stress
   - Shield Flux limit
   - Damper stress
   - Armature inner radius
   - Armature insulation thickness


START
INPUT
GENERATE OLD COST FUNCTION
GENERATE STEP SIZE IN ALL DIMENSIONS
CF
GENERATE NEW COST FUNCTION
COMPARE OLD AND NEW COSTS
NOT DONE
DONE
PRINT OUTPUT
EXIT

BLOCK DIAGRAM OF PROGRAM

Figure 3.1

See eq. 3.91 for the generation of the penalty functions.

The optimization approach works by taking each of the eight search variables separately, and attempting to find a local minimum of the value returned by CF for each variable. Three calls to CF are made for each variable, with the value of the variable incremented twice by a fixed value:

$$Y_1 = CF(V_o) \tag{3.1}$$

$$Y_2 = CF(V_o + T_w x\ DV) \tag{3.2}$$

$$Y_3 = CF(V_o + 2\ x\ T_w\ x\ DV) \tag{3.3}$$

A second order curve of the following form, when fit to these three points

$$Y(V) = aV^2 + bV + C \tag{3.4}$$

will have as its postition of zero slope

$$V^* = V_o + T_w DV \frac{3Y_1 - 4Y_2 + Y_3}{2Y_1 - 4Y_2 + 2Y_3} \tag{3.5}$$

This resulting position will be a minimum of that second order curve if the second derivative of Y with respect to V is greater than zero

$$\frac{\partial^2 Y}{\partial V^2} = Y_1 + Y_3 - 2Y_2 > 0 \tag{3.6}$$

The optimization routine then selects the "optimum" machine design based on the penalty functions generated in subroutine CF, which is fit to the curve of eq. (2.4) to find the minimum "cost" times "penalty". Following is a summary of the calculations performed in the main subroutine CF.

3.2 Subroutine CF

Subroutine CF utilizes two subroutines, CS and CM, which calculate the geometric parameters used in the inductance expressions.

The optimization variables or search variables,(see Table 3.1)

R_{fi}	is	field inner radius
T_{hf}	is	field thickness
G_{fk}	is	field-to-damper gap
T_{hk}	is	damper thickness
G_{ka}	is	damper-to-armature gap
T_{ha}	is	armature thickness
G_{as}	is	armature-to-core gap
I_f	is	field current density

Table 3.1

are passed into CF through the vector $\overline{V}$, which is the only argument into CF from the optimization program.

With the exception of the values of V and the returned value of CF, which is the penalized cost CF, all other variables used by CF are fully self-contained within the subroutine. All other values generated by CF and passed to the output are the optimum machine dimensions and characteristics.

3.2.1 Machine Length and Synchronous Reactance

The calculation of machine length and synchronous reactance is generalized by an arbitrary number of armature phases and the inclusion of an armature winding factor. This calculation is complicated because of a voltage drop in synchronous reactance over the unknown machine length, and by the effect of the end turns. The machine rating in volt-amperes is given by:

$$VA = N_{\phi a} V_t I_t \tag{3.7}$$

where

VA	is	rating in volt-amperes
$N_{\phi a}$	is	the number of armature phases
V_t	is	phase voltage (RMS)
I_t	is	phase current (RMS)

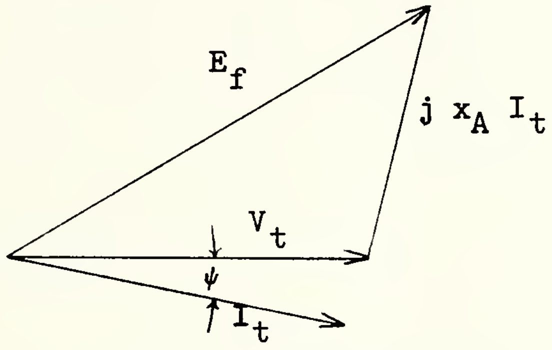
The RMS value of the internal voltage may be written as:

$$E_f = \frac{\omega M I_f}{\sqrt{2}} \tag{3.8}$$

where

E_f	is	internal voltage
M	is	field-armature mutual inductance, given by eq. (3.13)
I_f	is	field current
ω	is	electrical angular frequency

The relationship of E_f to V_t can be obtained from the phasor diagram for machine operation (see Fig. 3.1).



Complex Phasor Diagram

for

Operation as a Generator

Figure 3.2

The law of cosines is applied to the above diagram to yield:

$$E_f^2 = V_t^2 + x_A^2 I_t^2 + 2V_t x_A I_t \sin\psi \qquad (3.9)$$

where x_A is machine synchronous reactance in ohms:

$$x_A = \omega \frac{N_{\phi a}}{2} L_a \tag{3.10}$$

and ψ is power factor angle. L_a is the phase self-inductance, given by eq. (3.14). By dividing and then rearranging eq.(3.9) by E_f^2, the ratio between terminal voltage and internal voltage is obtained:

$$\left(\frac{V_t}{E_f}\right) = \sqrt{1 - x_a^2 \cos^2\psi} - x_a \sin\psi \tag{3.11}$$

where

$$x_a = \frac{x_a I_t}{E_f} \tag{3.12}$$

is the synchronous inductance normalized to internal voltage. The two inductances used here are:

$$M = \frac{32\, \ell_a \mu_o N_a N_f \sin\left(\frac{\theta_{wae}}{2}\right) \sin\left(\frac{\theta_{wfe}}{2}\right)(1-y^{p+2})}{P\pi\theta_{wae}\, \theta_{wfe}\, (1-y^2)\, (1-x^2)} \left[\frac{R_{fo}}{R_{ao}}\right]^p C_m k_{wa} \tag{3.13}$$

$$L_a = \frac{16\ell_{oa}\mu_o N_a^2 \sin^2\left(\frac{\theta_{wae}}{2}\right)}{P\pi\theta_{wae}^2\, (1-x^2)^2} C_s\, k_{wa}^2 \tag{3.14}$$

where

ℓ_a	is	active length for mutual coupling
ℓ_{oa}	is	active length for self-inductance
μ_o	is	permeability of free space
N_a	is	number of armature turns
N_f	is	number of field winding turns
θ_{wae}	is	armature phase winding angle
θ_{wfe}	is	field winding angle
x	is	armature radius ratio $x = \frac{R_{ai}}{R_{ao}}$
y	is	field radius ratio $y = \frac{R_{fi}}{R_{fo}}$
R_{fo}	is	field outer radius
R_{ao}	is	armature outer radius
C_m	is	the mutual coupling coefficient see eq.(3.30)
P	is	the number of Pole pairs
C_s	is	the self-inductance coefficient see eq.(3.31)
k_{wa}	is	the armature winding factor

The field and armature currents are related to current densities by:

$$I_f = \frac{J_f \, \theta_{wfe} \, R_{fo}^{\;2} \, (1-y^2)}{2N_{ft}} \tag{3.15}$$

$$I_a = \frac{J_a \, \theta_{wae} \, R_{ao}^{\;2} \, (1-x^2)}{2N_{at}} \tag{3.16}$$

Now, substituting eqs. (3.8),(3.11),(3.13),(3.14),(3.15) and (3.16) into eq.(3.7) and performing some manipulations yields:

$$VA = P_p\, a \left[\sqrt{1-x_a^{\,2} \cos^2\psi} - x_a \sin\psi \right] \qquad (3.17)$$

where

$$P_p = \frac{8 N_{\phi a}\, \omega\, \mu_o\, J_a J_f (1-y^{p+2}) R_{fo}^{\;2+p}\, R_{ao}^{\;2-p}\, C_m}{\sqrt{2\pi}}\, k_{wa}$$

$$\sin\left(\frac{\theta_{wae}}{2}\right) \sin\left(\frac{\theta_{wfe}}{2}\right) \qquad (3.18)$$

Substituting eqs.(3.8),(3.10),(3.13), and (3.14) into eq.(3.12) yields:

$$x_a = x_i \frac{\ell_{oa}}{\ell_a} \qquad (3.19)$$

where

$$x_i = \frac{\sqrt{2}\, N_{\phi a}}{4} \frac{J_a}{J_f} \frac{\sin\left(\frac{\theta_{wae}}{2}\right)}{\sin(\theta_{wfe})} \left[\frac{R_{ao}}{R_{fo}}\right]^{2+p} \frac{C_s}{C_m} \frac{k_{wa}}{(1-y^{2+p})} \qquad (3.20)$$

The effect of end turns on self-inductance can be represented by:

$$\ell_{oa} = \ell_a + \Delta \qquad (3.21)$$

The end turn correction length Δ is postulated to be:

$$\Delta = \left[\frac{R_{ao} + R_{ai}}{p} - \frac{R_{fo} + R_{fi}}{p} k_{bf\ell}\right] k_{b\ell} \qquad (3.22)$$

In this equation $k_{b\ell}$ is used to describe different end turn forms and the factor $k_{bf\ell}$ is used to assign part of the end region to mutual coupling.

Combining eqs.(3.19),(3.20) and (3.21) yields:

$$VA = P_p \ell_a \left[\sqrt{1 - x_i^2 \left[\frac{\ell_a + \Delta}{\ell_a}\right]^2 \cos^2\psi} - x_i \left[\frac{\ell_a + \Delta}{\ell_a}\right] \sin\psi\right] \qquad (3.23)$$

By defining:

$$\ell_z = \frac{VA}{P_p} \qquad (3.24)$$

and then dividing eq.(3.23) by VA, the following is obtained:

$$1 = \sqrt{\alpha^2 - x_i^2(\alpha+\beta)^2\cos^2\psi} - x_i(\alpha+\beta)\sin\psi \qquad (3.25)$$

where

$$\alpha = \frac{\ell_a}{\ell_z} \qquad (3.26)$$

$$\beta = \frac{\Delta}{\ell_z} \qquad (3.27)$$

Eq.(3.25) can be solved for α:

$$\alpha = a + \sqrt{a^2 + 1 + 2x_i\beta\sin\psi + x_i^2\beta^2} \qquad (3.28)$$

where

$$a = \frac{x_i^2\beta + x_i \sin\psi}{1 - x_i^2} \qquad (3.29)$$

Per-unit synchronous reactance based on terminal voltage is then determined to be:

$$x_d = \left[\frac{x_a}{\frac{V_t}{E_f}}\right]$$

3.2.2 Geometric Coefficient C_m and C_s

The geometric coefficient C_m is calculated by the subroutine CM, with arguments p,x and w. For mutual inductances involving the armature winding, C_m is found as follows:

$$w = \frac{R_{ao}}{R_s}$$

$$C_m = \tfrac{1}{8}(-\ln x + \tfrac{1}{4}(1-x^2)w^4) \qquad \text{if } p = 2$$

$$C_m = \frac{1-x^{2-p} + \frac{2-p}{2+p}(1-x^{2+p})w^{2p}}{4-p^2} \qquad \text{if } p \neq 2 \qquad (3.30)$$

The geometric coefficient C_s is calculated by CS with the arguments p,x and w for self inductance.

$$C_s = \frac{x^4 \log x}{2} + \frac{1-x^4}{8} + \frac{(1-x^4)^2}{16} w^4 \quad \text{if } p = 2$$

$$C_s = \frac{(2-p)4x^{p+2} + 3x^p + 2(\frac{2-p}{2+p})(1-x^{2+p})^2}{p(4-p^2)} w^{2p} \quad \text{if } p \neq 2 \tag{3.31}$$

The above procedure is used for the self-inductance of all windings, by substituting appropriate parameters for x and w.

Overall lengths for the damper and field winding are computed in the same fashion as for the armature. Bearing length is assumed to be damper length plus the length of the thermal distance pieces. The thermal distance piece length LTH, is an input constant.

3.2.3 Effective Current Density

As stated, the armature conductors are not aligned with the axis of the machine; therefore, the axial component of the current which produces the interaction is found by:

$$J_{ah} = J_a \cos \theta_h \tag{3.32}$$

where J_a is the total current density in the helical path, and θ_h is the helix angle:

$$\theta_h = \tan^{-1} \frac{\pi R_{ai}}{a} \qquad (3.33)$$

If x_i is computed according to eq.(3.20) and using total current density J_a, the internally based synchronous reactance will be found to be:

$$x_a = x_i \cos\theta_h (1 + \frac{\Delta}{a}) \qquad (3.34)$$

where Δ is given by eq.(3.22).

The machine length ℓ_a is found by:

$$\ell_a = \frac{VA}{P_p \cos\theta_h (\frac{V_t}{E_f})} \qquad (3.35)$$

where P_p is found by eq.(3.18) and using total current density J_a.

3.2.4 Transient and Subtransient Electrical Parameters

Transient reactance for the machine can be found

by:

$$x_d' = x_d \left[1 - \frac{M^2}{L_a L_f} \right] \tag{3.36}$$

The equation for L_f is the same as eq.(3.14) for L_a with the substitution of y for x, R_{fo} for R_{ao} and θ_{wfe} for θ_{wae}. Substituting these values into eq.(3.36) yields:

$$x_d' = x_d \left[1 - 4 \frac{\ell_a^{\,2} k_{wa}}{\ell_{oa} \ell_{of}} \frac{C_m^{\,2} (1-y^{p+2})^2}{C_s(p, x, R_{ao}/R_s) \; C_s(p, y, R_{fo}/R_s)} \left(\frac{R_{fo}}{R_{ao}}\right)^{2p} \right] \tag{3.37}$$

Subtransient reactance is given by:

$$x_d'' = x_d \left[1 - 2 \left(\frac{\ell_a^{\,2}}{\ell_{oa} \ell_{of}}\right) \frac{C_m^{\,2}}{C_s(p, x, w) \; C_s(p, z, R_{ko}/R_s)} \left(\frac{R_{ko}}{R_{ao}}\right)^{2p} (1-z^{p+2})^2 \right] \tag{3.38}$$

The dynamic performance of superconducting machines is

a very important aspect of the overall machine design. This is brought about by a conflict between adequate rotor shielding, which requires a high rotor conductivity and a damping of rotor swings, which requires a lower conductivity. The damper time constant T_s and the armature time constant T_a are given by:

$$T_s = \frac{\pi}{4} \mu_o R_{ko} (R_{ko} - R_{ki}) \sigma_k (1 + R_{ki}/R_{ko})^{2p} \qquad (3.39)$$

$$\begin{gathered} T_a = \frac{2\mu_o \sin^2(\frac{\theta_{wae}}{2}) \sigma_a \lambda_a R_{ao}^2 C_s(p,x,R_{ao}/R_s) N_{\phi a} k_{wa}^2}{\pi \theta_{wae} (1-x^2)} \\ \frac{x_d''}{x_d} \end{gathered} \qquad (3.40)$$

The open-circuit subtransient time constant is:

$$T_{do}'' = T_s \left(\frac{x_d' - x_d''}{x_d - x_d''}\right) \qquad (3.41)$$

3.2.5 Field Current Rise

An estimate must be made of transient field current

resulting after a fault or short circuit. The value calculated here, corresponding to maximum field current during a critical swing, is used later to determine if the field current is within limits.

Two assumptions are made to simplify the calculations:

1. Field flux is constant over the period of the swing.
2. There is no shielding of the field for this transient.

E_{fo} is voltage behind synchronous reactance corresponding to the operating condition in which:

I_{fo} is field current

δ_o is torque angle

I_{f1} and δ_1 correspond to the fault condition

The field current rise is:

$$\frac{I_{f1}}{I_{fo}} = \frac{2}{E_{fo}} \frac{x_d - x_d'}{x_d' + x_e} \cos\delta_o + 1 \qquad (3.42)$$

The initial torque angle is found by:

$$\delta_o = \sin^{-1} \left[\frac{p(x_d + x_e)}{V\, E_{fo}} \right] \qquad (3.43)$$

The values of E_{fo} and V_∞^2 are found from the following expressions:

$$E_{fo}^2 = V_t^2 + (x_d I_t)^2 + 2\, x_d I_t V_t \sin\psi \qquad (3.44)$$

$$V_\infty^2 = V_t^2 + (x_E I_t)^2 - 2\, x_E I_t V_t \sin\psi \qquad (3.45)$$

3.2.6 Torque Tube Thickness

The inner member of the rotor is a heavy-walled cylinder called the torque tube. The primary requirement on the torque tube is that the stresses be kept below the yield stress of the material. This yield criterion is necessary in order to avoid any fatigue failures or changes in dimensions which could result in a mechanically unbalanced rotor.

The computer program attempts to estimate the thinnest torque tube that will take the worst-case fault torque duty. During a fault, the radial forces generated will force the torque tube into an out of round condition. All circumferentially dependent loads are averaged and treated as uniformly distributed forces.

The max shear stress is given by:

$$\tau_{max} = \tau_s^2 + \left(\frac{\sigma_\theta}{2}\right)^2 \qquad (3.46)$$

The two components of stress are shear stress resulting from torque

$$\tau_s = \frac{2Tr}{\pi(R_{bo}^4 - R_{bi}^4)} \tag{3.47}$$

and tensile centrifugal stress

$$\sigma_\theta = \frac{3+\nu}{8} \rho \omega^2 \left[R_{bo}^2 + R_{bi}^2 + \frac{R_{bo}^2 R_{bi}^2}{r^2} - \frac{1+3\nu}{3+\nu} r^2 \right] \tag{3.48}$$

where r is the radius:

R_{bi} is inner radius of torque tube
R_{bo} is outer radius of torque tube
ρ is mass density for torque tube
ν is Poisson's ratio for torque tube
T is torque

The computer program tests the maximum stress eq.(3.46) at the inner and outer radii of the torque tube. It compares the larger of the two stresses with the stress limits which are an input to the program. The program will accept torque tube stresses between:

$$.95\ \tau_{\lim} \leq \tau_{\max} \leq \tau_{\lim} \qquad (3.49)$$

If the maximum stress is not within these limits, the program computes a new value of inner torque tube radius divided by the outer torque tube radius which is a ratio of torque tube thickness and then recomputes the maximum stress limits.

If eq.(3.47) is not satisfied after 250 tries, the programm assumes a solid shaft and computes the maximum stress in this shaft. The maximum stress level $\tau_{\max}$ will later be used in a penalty function for torque tube stresses.

3.2.7 Damper

The damper is a thin conducting cylinder located at the outermost diameter of the rotor. The principal functions of this damper shield are to shield the superconducting field winding from alternating magnetic fields and to damp the mechanical oscillation of the rotor. In the event of a terminal fault, the damper has to withstand the strong crushing and torque loads. These loads must be computed in order to insure adequate thickness of the damper. The force per unit area on the damper during a terminal fault is given by:

$$\sigma_r = \frac{\mu_o}{2}(H_{\theta o}{}^2 - H_{\theta i}{}^2) \tag{3.50}$$

$$\sigma_\theta = \mu_o(H_{\theta o} - H_{\theta i})H_r \tag{3.51}$$

In a magnetic field, where H_r is the radial component and the tangential components inside and outside the cylinder are $H_{\theta i}$ and $H_{\theta o}$ respectively.(8)

The magnitude of the fundamental component of the tangential field at the damper due to the average rms armature current density J_a is given by:

$$H_\theta = \frac{3\sqrt{2}}{\pi} \sin(\frac{\theta_{wae}}{2}) R_{ao} \left[1-x + \frac{1}{3}(1-x^3)(\frac{R_{ao}}{R_{mi}})^2 \right] J_a \tag{3.52}$$

The tangential field at the angle θ outside the damper due to the armature current immediately after a fault is:

$$H_{\theta a} = \frac{3\sqrt{2}}{\pi} \sin(\frac{\theta_{wae}}{2}) R_{ac} J_{ar} \left[1-x + \frac{1}{3}(1-x^3)(\frac{R_{ao}}{R_{mi}})^2 \right] \left[\frac{V_t}{x_d'''} \left[\cos(wt+\phi-\theta)-\cos(\phi-\theta)\right] + \cos(wt+\phi-\theta+\frac{\pi}{2}-\psi) \right] \tag{3.53}$$

The tangential field inside the damper due to the rated armature current, which is not affected by the fault, is given by:

$$H_{\theta ao} = \frac{3\sqrt{2}}{\pi} \sin(\frac{\theta_{wae}}{2}) R_{ao} J_{ar} \left[1-x + \frac{1}{3}(1-x^3)(\frac{R_{ao}}{R_{mi}})^2 \right]$$

$$\cos(wt + \phi - \theta + \frac{\pi}{2} - \psi) \qquad (3.54)$$

The tangential field at the damper, due to the field current, which is constant before and immediatley after the fault is:

$$H_{\theta f} = \frac{2}{3\pi} \sin(\frac{\theta_{wfe}}{2}) R_s (\frac{R_{fo}}{R_s})^3 (1-y^3) \left[1-(\frac{R_s}{R_{mi}})^2 \right] J_f$$

$$\cos(wt + \phi - \theta + \sigma) \qquad (3.55)$$

The current in the damper is induced so that the radial component of the total field is kept constant before and after the fault. Immediately after the fault, the field due to this induced current is:

$$H_{\theta s} = \left[\frac{1-(\frac{R_s}{R_{mi}})^2}{1+(\frac{R_s}{R_{mi}})^2} \right] \frac{3\sqrt{2}}{\pi} \sin(\frac{\theta_{wae}}{2}) R_{ao} \left[1-x + \frac{1}{3}(1-x^3)(\frac{R_{ao}}{R_{mi}})^2 \right]$$

$$J_{ar} \frac{V_t}{x_d'''} \left[\cos(wt + \phi - \theta) - \cos(\phi - \theta) \right] \qquad (3.56)$$

Adding up these components, the total tangential field outside the damper immediatley after a fault is obtained.

$$H_{\theta o} = H_{\theta a} + H_{\theta s} + H_{\theta f} \qquad (3.57)$$

The total tangential field for the inside is:

$$H_{\theta i} = H_{\theta f} + H_{\theta ao} \qquad (3.58)$$

To obtain the maximum value of σ_r, it is assumed that the maximum σ_r occurs when the traveling wave (sum of three terms which have ωt in eq.(3.57)) comes to the same phase as the standing wave ($\cos(\phi-\theta)$ terms in eq.(3.57).(8)

$$\sigma_r = \sigma_{r1} + \sigma_{r2} \cos 2(\phi - \theta + \gamma) \qquad (3.59)$$

where

$$\delta_{r1} = \frac{\mu_o}{4}(F^2 - D^2 - E^2) \qquad (3.60)$$

$$\delta_{r2} = \frac{\mu_o}{4}\sqrt{(F^2 - E^2 + D^2)^2 + 4E^2D^2}$$

$$\gamma = \frac{1}{2} \tan^{-1} \frac{2ED}{F^2 - E^2 + D^2} \qquad (3.61)$$

$$A = H_{ao} \sin\psi + \frac{2H_a}{1 + (\frac{R_s}{R_{mi}})^2} + H_f \cos \delta \qquad (3.62)$$

$$B = H_{ao} \cos\psi + H_f \sin \delta \qquad (3.63)$$

$$C = \frac{2H_a}{1 + (\frac{R_s}{R_{mi}})^2} \qquad (3.64)$$

$$D = H_{ao} \cos(\tan^{-1} \frac{B}{A} + \psi) - H_f \sin(\tan^{-1} \frac{B}{A} - \delta) \qquad (3.65)$$

$$E = -H_{ao} \sin(\tan^{-1} \frac{B}{A} + \psi) - H_f \cos(\tan^{-1} \frac{B}{A} - \delta) \qquad (3.66)$$

$$F = -\sqrt{A^2 + B^2} - C \qquad (3.67)$$

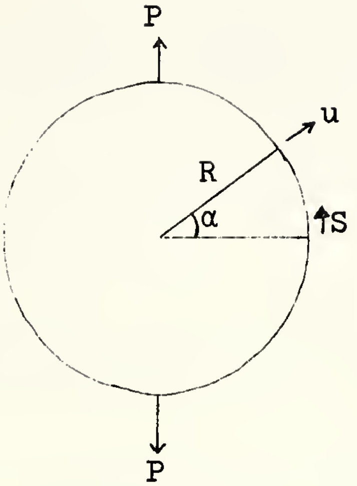
$$M = \frac{PR}{2} (\cos\alpha - \frac{2}{\pi}) \qquad (3.68)$$

For concentrated radial force as shown in Fig. 3.3, the radial displacement u and the bending moment M are given by:

$$\frac{d^2u}{ds^2} + \frac{u}{R^2} = - \frac{M}{EI} \qquad (3.69)$$

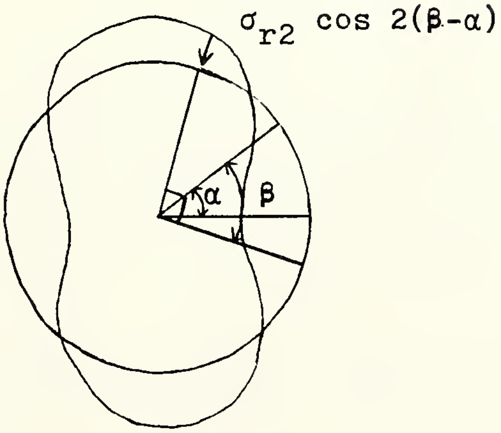
where M is found from eq.(3.68). For the bending stresses:

$$\delta_b = \frac{M}{Z} = \frac{PR}{2Z} (\cos\alpha - \frac{2}{\pi}) \qquad (3.70)$$



Concentrated Radial Force
On The Damper

Figure 3.3



Distributed Radial Force
On The Damper

Figure 3.4

The deflection is then solved:

$$u = \frac{PR^3}{\pi EI} - \frac{PR^3}{4EI}\,\alpha \sin\alpha - \frac{PR^3}{4EI}\cos\alpha \qquad (3.71)$$

For the distributed load as shown in Fig. 3.4, the deflection at angle α is:

$$u(\alpha) = \frac{4}{3}\,\frac{\sigma_{r2}\;R^4}{E_t^3}\cos 2\alpha \qquad (3.72)$$

where t is the thickness of the damper.
The bending stress in Fig. 3.4 is then given by:

$$\sigma_b = \frac{2\sigma_{r2}\;R^2}{t^2}\cos 2\alpha \qquad (3.73)$$

Adding the deflection and the stress due to the centrifugal force and the uniform magnetic force to eqs.(3.72) and(3.73) the total deflection and stress are obtained.

$$\sigma_{total} = -\frac{\sigma_{r1}\;R}{t} + \frac{2\sigma_{r2}\;R^2}{t^2}\cos 2\alpha + \rho\,\omega^2\,R^2 \qquad (3.74)$$

$$u_{total} = -\frac{\sigma_{r1}\cdot R^2}{E_t} + \frac{4\sigma_{r2}\;R^4}{3E_t^3}\cos 2\alpha + \frac{\rho R^3\,\omega^2}{E} \qquad (3.75)$$

Using eq.(3.74), the thickness t of the damper can be calculated such that the maximum allowable stress and deflection will not be exceeded during a terminal fault.

3.2.8 Negative Sequence Losses

Negative sequence currents in the stator produce a magnetic field distribution which rotates in a sense opposite that of the rotor. Since the damper is a good shield, it excludes this magnetic field from the rotor and must match this field at its surface. The magnetic field at the surface of the rotor is given by:

$$H = J_a I_2 \frac{4}{\pi} \frac{\sin(\frac{\theta_{wae}}{2})\, R_{ko}{}^{p-1}\, R_{ao}{}^{2-p}\, p(2+p)}{1 + (\frac{R_{ko}}{R_s})^{2p}} C_m(p, x, \frac{R_{ao}}{R_s}) \tag{3.76}$$

The current density in the damper is:

$$J_k = \frac{H_\theta}{t_k}$$

The negative sequence loss in the damper is then given by:

$$P_{sh} = \frac{J_k{}^2\, \theta_{wke}\, R_{ko}{}^2 (1-Z^2)}{\sigma_k\, \lambda_k\, p} \ell_k\, N_{\emptyset k} \tag{3.77}$$

where

$$\ell_k = (\ell_a + \frac{R_{ko} - R_{ki}}{p}) \qquad (3.78)$$

3.2.9 Armature Losses

Conduction losses in the armature are calculated by:

$$P_a = \frac{J_a^{\,2}}{\sigma_a \lambda_a} \theta_{wae} N_{\phi a} R_{ao}^{\,2} (1-x^2) \ell_{oa} \qquad (3.80)$$

3.2.10 Field at Shield Radius

This is the radial magnetic flux density at the inner radius, R_s, of the stator core:

$$B_{rs} = \frac{4\mu_o J_f \sin(\frac{\theta_{wfe}}{2})}{\pi(2+p)} R_s (\frac{R_{fo}}{R_s})^{2+p} (1-y^{p+2}) \qquad (3.81)$$

The core outer radius is then found by using the magnetic flux density and the inner radius:

$$R_{so} = R_s (1 + \frac{B_{rs}}{B_{smax} p}) \qquad (3.82)$$

3.2.11 Field at an Inner Corner of Field Winding

The highest field intensity is assumed to occur at the inner radius of the field winding, and at positions

adjacent to pole faces. The radial and azimuthal fields are calculated by:

$$H_r = \sum_n H_n \sin(\frac{n}{2}\,\theta_{wfe}) \tag{3.83}$$

$$H_\theta = \sum_n H_n \cos(\frac{n}{2}\,\theta_{wfe}) \tag{3.84}$$

where

$$H_n = \frac{2J_f}{\pi}\,\frac{2+np}{n}\,R_{fi}\,y^{np-2}\,C_m(np, y, R_{fo}/R_s) \tag{3.85}$$

The maximum field intensity is then:

$$H_{max} = \sqrt{H_r^{\,2} + H_\theta^{\,2}} \tag{3.86}$$

3.2.12 Rotor Critical Speed

The rotor is assumed to be a beam of constant stiffness and mass, simply supported at both ends for the purpose of estimating rotor first-critical speed. The first critical frequency is then:

$$\omega_c = 9.875\sqrt{\frac{EI}{\ell_{br}^{\,4}\,M}} \tag{3.87}$$

ℓ_{br} is bearing length

M is mass per unit length

It is further assumed that the only stiffness is provided by the torque tube:

$$I = \frac{\pi}{4} (R_{fi}^{4} - R_{bi}^{4}) \tag{3.88}$$

The mass per unit length includes the entire rotor which consist of the torque tube, field windings, hoop binding material for field winding, shield and damper. The length is assumed to be the bearing length ℓ_{br}.

3.2.13 Stator Core Losses

It has been assumed that all of the core is operating at roughly a uniform flux density, and hence a uniform loss density.

$$P_{core} = M_{core} P_m \tag{3.89}$$

where:

M_{core} is the total core mass

P_m is dissipation per unit mass

Core dissipation per unit mass is estimated to be a simple power function of flux density:

$$P_m = P_o(\frac{B_{rs}}{B_{smax}})^{\gamma} \tag{3.90}$$

where:

B_{rs} is computed in eq.(3.81)

B_{smax}	is	core flux limit
P_o	is	dissipation per unit mass when the core is operating at its limiting flux density
γ		reflects the rate of change of loss with flux density

All the above, except for B_{rs} , are input variables.

3.2.14 Cost Function

The non-penalized cost is the cost of the machine in weight. The weight includes the support tube, damper, armature windings, field winding, iron in the core and binding material. A weight loss in KG/watt is also found.

3.2.15 Penalty Functions

The cost of the machine, such as weight, current losses or stresses is modified by multiplying by a set of penalty functions. These are of the form:

$$F_p = .9 + .1(Q/Q_\ell)^{15} \tag{3.91}$$

where:

Q	is	quantity being penalized
Q_ℓ	is	the maximum limit for that quantity

This quantity is close to 1 for values of Q less than Q_ℓ , but becomes very large for values of Q greater than Q_ℓ.

The field-current-limit penalty function is slightly different. The extremes of magnetic field and current density in the field winding are H_{max} eq.(3.86) and $J_f I_{fl}$ eq.(3.42). This combination must be compared to the H-J curve. The magnetic field-current density curve is approximated by a six-segment piece-wise-linear curve as shown in Fig. 3.5. The data representing this curve is input at two five-element vectors, one representing the values of H, and the other representing the vlues of J.

H-J CURVE

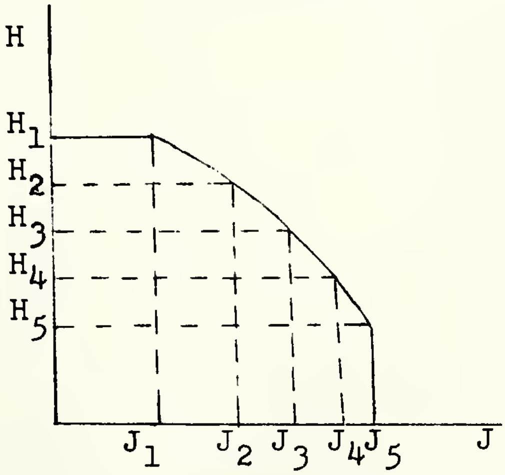


Figure 3.5

If H_{max} is greater than H_1, the field-current-limit penalty function is set to a very large number. If H_{max}

falls between the values of H_1 and H_5, the computer program does a direct linear interpolation to find the critical current density J. If H_{max} is less than H_5, the critical current density is set to J_5.

The final penalized cost function CF, is the product of the cost and all of the penalty functions. This is the value returned by CF to the optimization main program. The value of CF is used as a figure of merit for each different machine iteration. The machine selected by the program is the one with the lowest value of CF.

CHAPTER 4

Superconducting Propulsion Plant

4.1 Introduction

Chater 1 has covered the basic machinery configuration of the electric propulsion system. The actual design of the superconducting machine is described in Chapter 3. The "optimized" electric machines and the associated subsystems necessary to complete the entire propulsion system will be discussed here.

The output of the optimization program is an "optimum machine" only for one particular set of assumptions as to machine design requirements and costs. The fixed inputs common to both the generator and the motor are given in Appendix F. The initial guess for the search variables or optimization variables are shown in Appendix D. The combination of these inputs yield the optimized generator design and motor design described in Sections 4.2 and 4.3 of this chapter. The requirements of the machines described in sections 4.2 and 4.3 are then used to determine the characteristics of the remaining subsystems in Section 4.4.

4.2 Superconducting Generator

The first step of the electric propulsion system design process was the design of a 20,000 HP 3,600 RPM

synchronous generator driven by 20,000 HP gas turbines. A summary of the results are shown in Table 4.1. The detailed computer output results are contained in Appendix B.

All of the machine dimensions, machine volume and the weight of active parts are computed by the computer program. A steel outer shell for machine structure support was included as additional weight and volume, resulting in the total machine volume and weight. (The computer program did not compute the outer shell characteristics. Provisions can be made at a later date to include this in the program.) The steel outer shell was assumed to be one-half inch thick (.0127 M) plus the structural supports required to mount the machine to a foundation. The end bells were assumed to be 3/4 inch thick steel and the same diameter as the outer diameter of the newly added steel shell.

Using these new dimensions, the new volume is calculated to be 1.1 M^3 and the new total weight is 4309.2 KG. The weight of 4309.2 KG also takes into account the weight of the generator feet and steel supports necessary to mount the machine to its foundation.

4.3 Superconducting Motor

The next output of the optimization design procedure was a 40,000 horsepower, 200 RPM synchronous motor. A

A SUMMARY OF RESULTS
FOR
A 20,000 HP GENERATOR

Table 4.1

Mechanical Rating		20,107 HP	
Electrical Rating		15 MVA	
Mechanical Speed		3.600 RPM	
Number of Poles		2	
Active Length		.69 M	27.2 IN
Overall Length		1.52 M	59.9 IN
Field Winding	Inside Diameter	.19 M	7.7 IN
	Outside Diameter	.25 M	9.8 IN
Armature Winding	Inside Diameter	.43 M	16.9 IN
	Outside Diameter	.62 M	24.4 IN
Iron Shield	Inside Diameter	.67 M	26.4 IN
	Outside Diameter	.92 M	36.2 IN
Machine Volume		1.01 M^3	35.7 FT^3
Weight of Active Parts		3,175.4 KG	3.1 T
Total Machine Volume		1.1 M^3	38.8 FT^3
Shell,EndBells,Bearings & Structural Support		1,133.8 KG	.9 T
Total Weight of Machine		4,309.2 KG	4.0 T
Synchronous Reactance		1.38	
Transient Reactance		1.18	
Subtransient Reactance		1.20	

summary of the results for the 40,000 HP motor are shown in Table 4.2. The detailed computer output for the motor is contained in Appendix G.

The dimensions of the active machine parts are computed by the optimization program, while the weight and volume of the steel structural shell and the weight of the motor feet were added to the computer output to produce the total machine weight and volume. For the motor, the steel outer shell was assumed to be 3/4 inches thick and the end bells 1 inch thick. The structural support of the motor is heavier than that for the generators because the motor must support the high torque loads associated with the propeller providing thrust to move the ship through the water.

The summary of results for the 30,000 HP motor are shown in Table 4.3. The 30,000 HP motor was designed when it became necessary to reduce the size of the ship's propulsion plant from 80,000 shaft horsepower to 60,000 shaft horsepower. Chapter 5 Sections 5.3.1 and 5.3.2 explain why the installed shaft horsepower was reduced. The total machine weight and volume were computed in the same manner as that for the 40,000 HP motor. The computer output for the 30,000 HP motor is contained in Appendix D.

4.4 Subsystems of Superconducting Machinery

Cryogenic refrigeration systems are necessary to

A SUMMARY OF RESULTS
FOR
A 40,000 HP MOTOR

Table 4.2

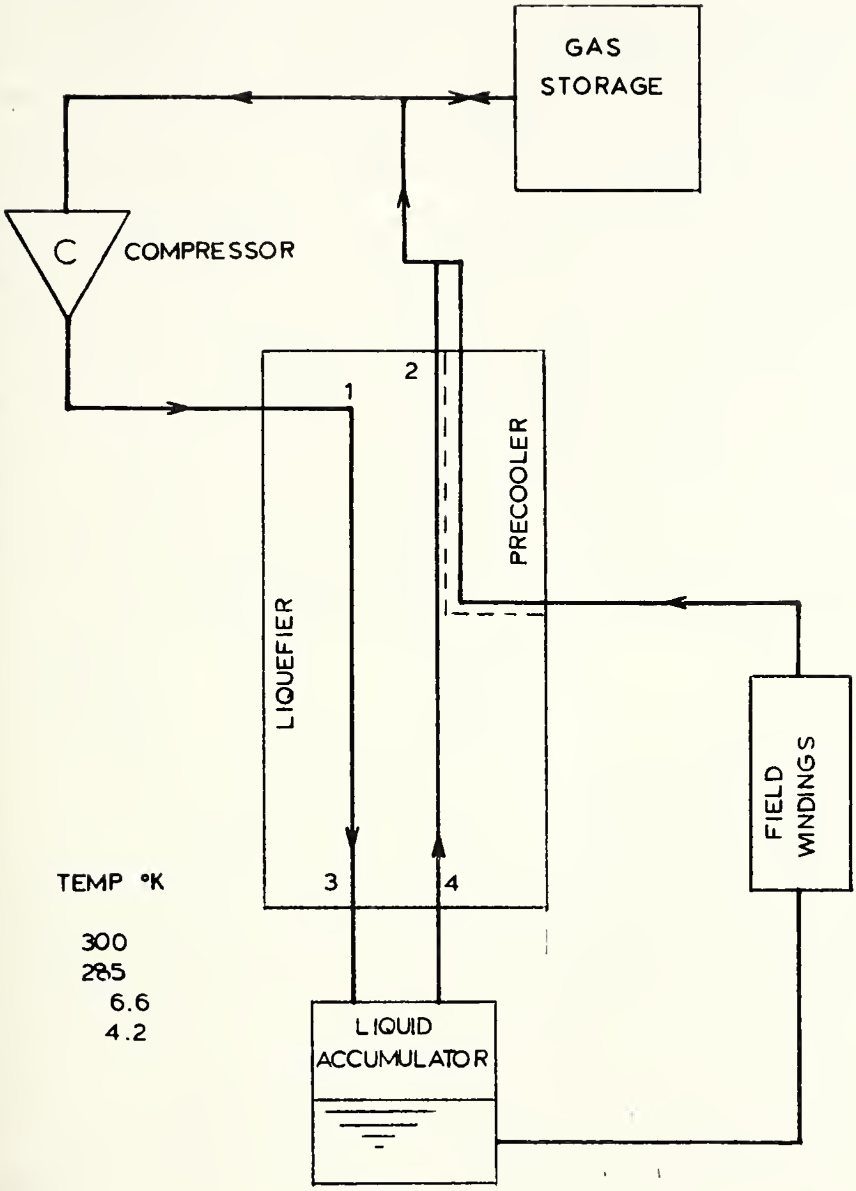
Mechanical Rating		40,214 HP	
Electrical Rating		30 MVA	
Mechanical Speed		200 RPM	
Number of Poles		6	
Active length		1.51 M	59.4 IN
Overall Length		2.35 M	92.4 IN
Field Winding	Inside Diameter	.86 M	34.0 IN
	Outside Diameter	.93 M	36.4 IN
Armature Winding	Inside Diameter	1.11 M	43.7 IN
	Outside Diameter	1.46 M	57.4 IN
Iron Shield	Inside Diameter	1.52 M	59.9 IN
	Outside Diameter	1.73 M	68.2 IN
Machine Volume		5.52 M^3	195.3 FT^3
Weight of Active Parts		13,394.13 KG	13.2 T
Total Machine Volume		6.01 M^3	212.8 FT^3
Shell,EndBells,Bearings & Structural Support		1948.17 KG	1.9 T
Total Weight of Machine		15,342.3 KG	15.1 T
Synchronous Reactance		1.01	
Transient Reactance		.87	
Subtransient Reactance		.86	

A SUMMARY OF RESULTS
FOR
A 30,000 HP MOTOR
Table 4.3

Mechanical Rating		30,161 HP	
Electrical Rating		23 MVA	
Mechanical Speed		200	
Number of Poles		6	
Active Length		1.19 M	46.85 IN
Overall Length		2.01 M	79.1 IN
Field Winding	Inside Diameter	.79 M	30.94 IN
	Outside Diameter	.86 M	33.86 IN
Armature Winding	Inside Diameter	1.05 M	41.15 IN
	Outside Diameter	1.40 M	55.1 IN
Iron Shield	Inside Diameter	1.46 M	57.56 IN
	Outside Diameter	1.67 M	65.71 IN
Machine Volume		4.68 M^3	165.6 FT^3
Weight of Active Parts		10,577.7 KG	10.4 T
Total Machine Volume		4.68 M^3	165.6 FT^3
Shell, EndBells, Bearings & Structural Support		1,689.2 KG	1.6 T
Total Weight of Machine		12,266.9 KG	12 T
Synchronous Reactance		.98	
Transient Reactance		.87	
Subtransient Reactance		.86	

provide the helium for super-cooling the previously designed motors and generators. A diagram of a sample refrigerator/liquefier system is shown in Figure 4.1. The liquefier produces liquid helium which is stored in the liquid accumulator. The liquid helium is piped directly from the liquid accumulator to the superconducting field winding where it provides the necessary cooling by expanding back into a vapor. The returning helium vapor from the field winding passes through a precooler in the Liquefier, increasing the overall cycle effeciency. At present, most of the high capacity helium refrigeration units in use have been constructed for fixed installations, where weight and size are of secondary importance. The fixed installation type of compressors are a low-speed reciprocating compressor of bulky construction. They generally require massive foundations because of the reciprocating loads. Machinery of this size is totally unacceptable for shipboard use, where weight and size are at a premium.

The rotary compressor is a new entry to the field of helium refrigeration systems which will overcome the disadvantages of the reciprocating compressors. At present, there is not a great deal of information concerning high capacity rotary units. Experiments at MIT and elsewhere(1) have produced similar results as to the size,



STATION	TEMP °K
1	300
2	285
3	6.6
4	4.2

HELIUM LIQUEFIER/REFRIGERATOR DIAGRAM

Figure 4.1

weight and operating characteristics of the rotary compressor necessary to supply the cooling requirements of the motors and generators designed in this thesis.

The cooling requirement for the superconducting machines is an input to the program. This input, RP, is a penalty function for cryogenic refrigeration based on specific power consuption (watts input per watt at 4.2° K). Based on experience at MIT, the value of RP is assumed to be 1000. Using this value for specific power consumption of watts/watt cooling capacity, the required capacity in watts for the helium refrigerator can be determined.(1)

Capacity	Weight	Volume
10 watts	2000 lb.	100 ft^3

A refrigeration unit of the above dimensions would be used to supply the cooling requirements for one superconducting machine. Four generators and two motors would then require the use of six refrigerators of 10 watt capacity. Cross-connect capabilities could also be included as a backup for each system. If the liquefier/refrigerator system for one of the superconducting machines should suffer a breakdown, the appropriate cross-connects could be made and the unit in question would be cooled by liquid helium from another machine's liquefier/refrigerator.

4.4.1 Cable System

Marine cable systems used for connecting main generators to the main propulsion motors are sized for the allowable losses caused by joule effects. Cable weight can be a significant component in electrical propulsion systems. The cable weight depends on the voltage, current and allowable resistance per length. The advantage of ac propulsion systems over dc propulsion systems is that significantly higher voltages can be used. Higher voltage systems require a lighter cable, which is important in systems requiring minimum weight and volume propulsion machinery.

Cables for ac propulsion systems have been studied to show the relationship between weights and losses. These studies indicate that a light-weight cable system is possible with air-cooled cables,(1) see Table 4.4. The results in Table 4.4 are based on an allowable voltage drop of 9.8 V/100 ft. The area shown in Table 4.4 is the total copper cross-section area necessary to carry the 3-phase current at the given voltage. A 6900 volt system was used to produce the lightest weight cabling system. At 6900 volts, the maximum current will be 1,260 amps and the maximum transmission loss will be 28 KW per 100 ft., resulting in a .1 percent power loss.

Table 4.4

Voltage	Current	Area	Weight	Loss
4160 V_{ac}	2.100 A	1.56 in^2	6 lb/ft	45 KW/100 ft
6900 V_{ac}	1.260 A	1.04 in^2	4 lb/ft	28 KW/100 ft

For a 3-phase ac system, three conductors of the combined size and weight given above must be used to transmit power from the generators to the motors. This works out for a single conductor to be .384 inches in diameter and 1.33 lbs/ft. The weight of the conductor is further increased by about 40 percent with the addition of armor, lead shield and insulation. Each conductor is also surrounded by a 4 inch conduit which provides forced-air cooling and an added margin of insulation. If this conduit were constructed out of aluminum, it would weigh approximately .62 lb/ft for each conductor. Adding all of the weight together results in a total weight for the three conductors of 7.46 lb/ft.

4.4.2 Switch Gear and Control Units

There is very little information on full scale switch gear such as would be used on shipboard with superconducting electric machinery. Most of the technological work performed to date has been on laboratory size machinery, the results of which can be used to

predict the size and weight of the full scale machinery. The product of one such study by Rains(15) indicates that the switch gear will weigh approximately 2.9 tons and occupy approximately 600 ft^3. The switch gear and control units consist of the actual switching mechanism which controls the direction of the motor and an electric converter which controls the speed of the motor. The electronic converter will most likely be of the cycloconverter type. A cycloconverter is a solid state device that converts three-phase fixed frequency power to three-phase variable frequency power. The frequency of the output power from the cycloconverter directly controls the speed of the motor. A cycloconverter of sufficient power rating to accomodate a 40,000 HP motor will weigh approximately 3.9 tons and require 200 ft^3. Two cycloconverters and the switch gear will occupy 1000 ft^3 and weigh approximately 10.7 tons. This study also indicates that there will be 19.2 tons of miscellaneous equipment which will be added to cover items omitted from this thesis.

CHAPTER 5

COMPARISON OF ELECTRIC DRIVE WITH MECHANICAL DRIVE FOR SHIP PROPULSION

5.1 Introduction

The size and weight of the machinery components required to convert the propulsion plant to electric machinery were calculated in Chapter Four. In this chapter, these components will be combined with the remainder of the propulsion machinery to predict the resultant size and weight of the new electric propulsion system. The new system will be compared to the old mechanical drive system to measure the overall savings produced by the superconducting electric propulsion system. The comparison will be made for two different baseline ships as described in Chapter One. The first being the Model Baseline and the second the DD963 Baseline.

The Model Baseline is the DD963 as synthesized on the ship synthesis model(14) without the excess volume present in the current DD963 design. The DD963 Baseline is the DD963 as synthesized with all of the excess volume included in the design. A brief description of the Ship Synthesis Model for Naval Surface Ships,(14) along with a sample input and program output is shown in Appendix H. Table 5.1 contains the computer synthesized characteristics

Table 5.1

CHARACTERISTICS OF MODEL BASELINE AND DD963 BASELINE

CHARACTERISTIC	MODEL BASELINE	DD963 BASELINE
Max. Sustained Speed, knots	33.9	32.9
Sustained Speed SHP, horsepower	80,000	80,000
Endurance Speed, knots	20	20
Endurance Speed SHP, horsepower	10,548	11,483
Length between perpendiculars, ft. (LBP)	529	529
Beam, ft. (B)	54.6	55.8
Draft, ft. (T)	16.8	18.8
C_p	.59	.59
C_x	.83	.83
VCG Full Load, ft.	21.96	22.02
GM/B	.10	.10
Average Depth, ft.	40.03	40.67
Accomodations	298	298
KW Installed	6000	6000
Full Load Displacement, tons (Δ)	6906	7885
Light Ship Displacement, tons	4936.7	5827
Variable Loads Weight, tons	1868.8	1959
WTGP1, tons	2465.2	3137.1
WTGP2, tons	789.2	789.2
WTGP3, tons	282.7	296.8
WTGP4, tons	207.4	250.3
WTGP5, tons	569.1	739.8
WTGP6, tons	499.8	454.3
WTGP7, tons	159.2	159.2
Weight Margin, tons	100	100
Total Internal Volume, cu.ft. (∇_t)	945,470	1,013,880
Hull Volume, cu.ft. (∇_h)	761,020	772,581
Superstructure Volume, cu.ft. (∇_{ss})	184,449	241,298
Full Load Ship Density, lbs/cu.ft.	16.36	17.42
Military Mission Volume, cu.ft.	110,753	159,298
Personnel Volume, cu.ft.	251,990	251,990
Ship Ops Volume, cu.ft.	582,728	602,592
Payload Volume Fraction (VOL PAY/ ∇)	.12	.16
Personnel Volume Fraction (VOL PERS/ ∇)	.27	.25
Ships Ops Volume Fraction (VOL OPS/ ∇)	.62	.59
Payload Weight Fraction (W PAY/ Δ)	.05	.05
Personnel Weight Fraction (W PERS/ Δ)	.04	.03
Ship Ops Weight Fraction (W OPS/ Δ)	.47	.44

for each of these two ships.

In Table 5.1, Weight Groups 2 and 7 (WTGP2 and WTGP7) are the same for both ships, because the same propulsion plant (WTGP2) in type and horsepower and the same armament (WTGP7) was specified for both ships. The volume (172,736 cu.ft.) and weight (789.2 tons) for WTGP2 will be used as a baseline for estimating the new volume and weight of WTGP2 with superconducting electric machinery. WTGP2 is only one of several groups that comprise the entire Machinery System. The remaining groups must also be examined for changes resululting from a conversion to an electric propulsion plant. See Appendix I for a complete listing of the contents of each weight group.

The Machinery System is composed of the following:

Machinery Box

Uptakes

Shafting, Bearings and Propellers

Maneuvering

Ventilation

The Machinery Box can be further broken down into the following groups:

WEIGHT GROUP 2-PROPULSION

Propulsion Units
Combustion Air Supply
Propulsion Control Equipment

WEIGHT GROUP 2-PROPULSION (cont'd)

Fuel Oil Service Systems
Lubricating Oil System
Propulsion Operating Fluids

WEIGHT GROUP 3-ELECTRIC PLANT

Electric Power Generation
Power Distribution Switchboards
Electric Power Generator Fluids

WEIGHT GROUP 5-AUXILIARY SYSTEMS

Air-Conditioning Systems
Refrigerating Spaces, Plant & Equipment
Aviation Fuel & Lube Oil System, Sewage System
Compressed Air System
Auxiliary Steam, Exhaust Steam & Steam Drains
Distilling Plant
Auxiliary System Operating Fluids

WEIGHT GROUP 6-OUTFIT AND FURNISHINGS

Ladders & Gratings

Weight Groups 3,5 and 6 will not be directly affected by the introduction of an electric propulsion system as none of the machinery components for these groups will be physically changed or replaced. The only changes will come from secondary effects as a result of the physical dimensions of the ship being modified to accomodate a smaller and lighter weight propulsion system.

The uptakes will change is weight and volume only if

the number or size of propulsion unit gas turbines are changed, or if electric propulsion allows a major rearrangement of the machinery spaces. The electric plant gas turbine's requirements are also considered when sizing the uptakes.

The propellers, shafting and bearings will be directly affected by the modification to the electric propulsion. The Controllable-Reversable Pitch (CRP) propeller will be replaced by a lighter fixed pitch propeller. Shafting and bearings will be greatly reduced, as the electric motors will be coupled to the propellers through significantly shorter shafts. The majority of the weight for shafting and propellers and all of the volume for separate shaft alleys will be eliminated.

Maneuvering is comprised of steering systems and rudders which will not change for either ship when modified to electric propulsion. Maneuvering is a function of ship size and will vary only slightly as ship volume and displacement are changed when the propulsion system is modified.

Table 5.2 shows the volume and weight breakdown for the machinery system. All major changes in the volume and weight of the machinery system will come from changes in the machinery box, uptakes, shafting, bearings and propellers. The majority of the weight and volume changes

Table 5.2

VOLUME AND WEIGHT OF MACHINERY SYSTEM FOR MODEL BASELINE AND DD963 BASELINE

CHARACTERISTIC	MODEL BASELINE	DD963 BASELINE
Machinery System Volume, cu.ft.	293,597	292,801
Machinery Box Volume, cu.ft.	195,955	195,955
Uptakes Volume, cu.ft.	49,150	49,150
Shafting, Bearings & Propellers, cu.ft.	3,848	3,848
Maneuvering Volume, cu.ft.	6,996	6,996
Ventilation Volume, cu.ft.	37,648	36,852
VOL MACH SYS/∇	.31	.29
VOL MACH BOX/∇	.21	.19
VOL UPTAKES/∇	.05	.05
VOL Shafting, Bearings & Propellers/∇	.004	.004
VOL Maneuvering/∇	.007	.007
VOL Ventilation/∇	.036	.036
Machinery System Weight, tons	1259.1	1205.7
Machinery Box Weight, tons	722.2	697.3
Uptakes Weight, tons	130.5	130.5
Shafting, Bearing & Propellers Weight, tons	253.1	253.1
Maneuvering Weight, tons	81.7	66.0
Ventilation Weight, tons	71.6	58.7
Weight Mach Sys/DISPLACEMENT	.16	.18
Weight Mach Box/DISPLACEMENT	.090	.10
Weight Uptakes/ DISPLACEMENT	.017	.019
Weight Shafting, Bearings & Propellers/ DISPLACEMENT	.033	.037
Weight Maneuvering/DISPLACEMENT	.011	.010
Weight Ventilation/DISPLACEMENT	.009	.009

in the machinery box will result from WTGP2 variations.

5.2 Conversion to an Electric Propulsion Machinery System

The results of Chapter 4 are used to size the machinery system by modifying the propulsion system with superconducting electric machines. The new weight and volume of the machinery system were used as input to the ship synthesis model(14) to determine the impact on the overall ship system. The preliminary output from the synthesis process indicated that a baseline ship with four gas turbines converted directly to electric drive would not meet the no-change-in-payload, sustained speed or endurance range requirements as set forth in Chapter 1.

When the volume for the propulsion system went down, the volume for the payload went up because the size of the ship remained constant. Extra volume for the payload is unuseable when a ship is weight limited. More payload in the form of extra weight cannot really be added to take advantage of this extra volume. If this volume were to remain in the ship, it would only serve to make the present configuration of the ship space inefficient and wasteful.

The sustained speed could be met within the tolerances of the ship synthesis model itself. The top speed of the modified ships varied by less than 2%. A 2% change can be considered to essentially meet the no-increase in top

speed criteria.

By far, the largest deviation from the baseline characteristics was in the endurance range, which increased up to 25%. (Section 4.3 contains the calculations for the endurance range.) A range increase of this amount was unsatisfactory when compared to the inital criteria of no-range change allowed in the modified ship. To keep the range the same, over 200 tons of fuel can be removed. To meet the no-change in mission performance restrictions on the modified ship, a smaller three-engined ship with less horsepower was then investigated to determine if it could take advantage of this fuel weight savings.

The results from Chapter 4 are summed up in Table 5.3 for the four-gas turbine, four-generator, two-motor propulsion system and the three-gas turbine, three-generator, two-motor propulsion system. The four-engined propulsion system at 504.1 tons is 36% lighter than the baseline propulsion system of 789.2 tons. A 49% weight savings is realized by the 401.2 ton three-engined propulsion system. The volume occupied by Group 2 propulsion machinery is not given in any references. Reference 10 does contain machinery room arrangement plans without specific dimensions being listed. The specific dimensions of the gas turbines are listed and could be used as a reference for measuring the dimensions of the machinery

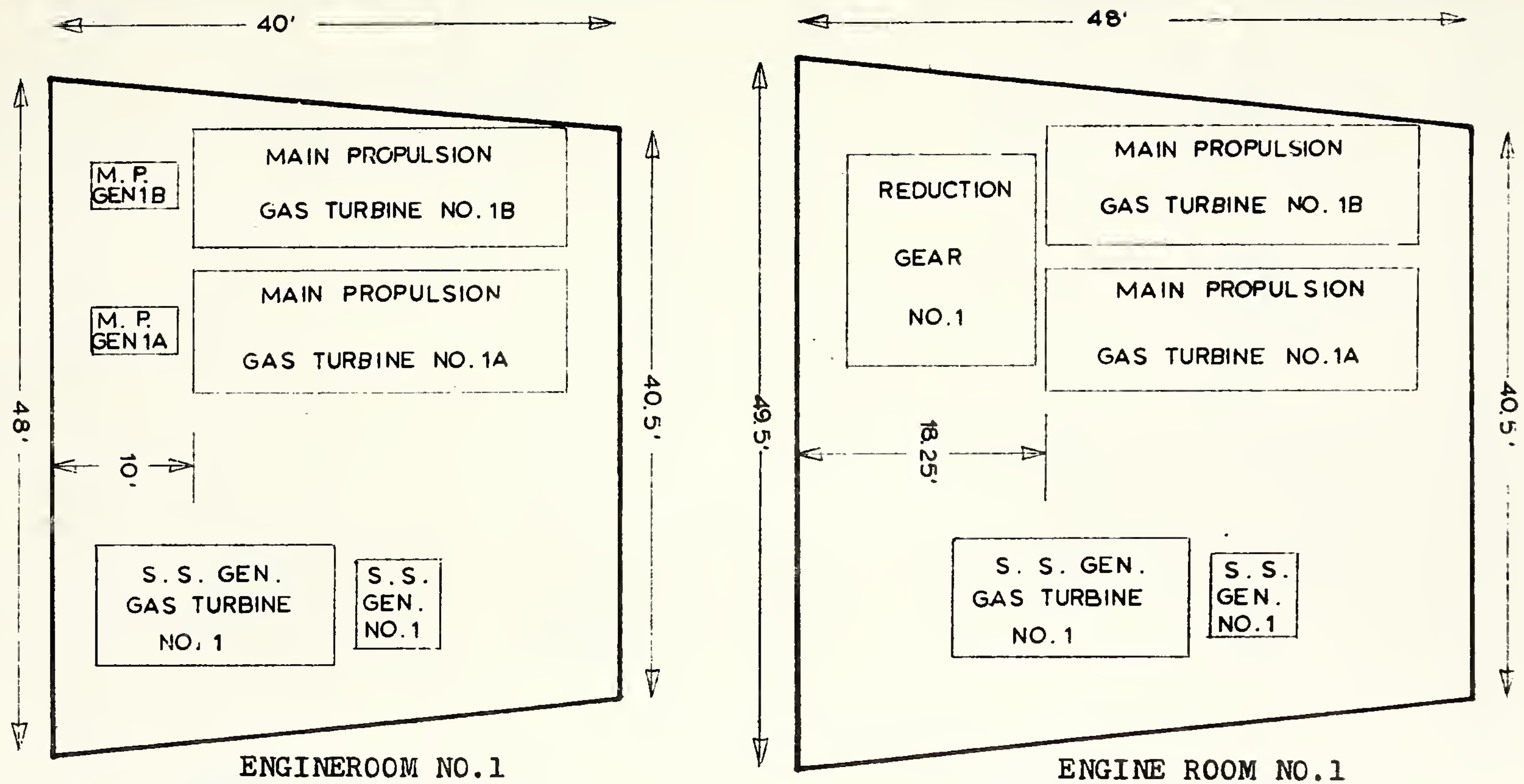
Table 5.3

WTGP2 WEIGHTS FOR BASELINE SHIP, FOUR-ENGINED AND THREE-ENGINED ELECTRIC PROPULSION SYSTEMS

CHARACTERISTIC	BASELINE	4-ENG. SHIP	3-ENG. SHIP
Gas Turbines		81.25	60.9
Generators		16.0	12.0
Motors		30.2	23
Cryogenic System		5.36	4.5
Foundations		12.3	9.3
PROPULSION UNITS, TONS	244.14	145.11	109.7
Shafting & Bearings		13.6	13.6
Propellers		36	36
Cabling (400 ft.)		1.33	1.0
SHAFTING, BEARINGS & PROPELLERS, TONS	253.1	50.93	50.6
Combustion Air System, tons	58.3	58.3	43.8
Uptakes, tons	130.5	130.5	98.1
Switch Gear		10.7	8.5
PROPULSION CONTROL, TONS	10.97	19.2	15.55
Fuel Oil Service System, tons	10.1	10.1	7.4
Lube Oil System, tons	31.2	20.0	16.1
Repair Parts, tons	8.5	8.5	8.5
Operating Fluids, tons	42.2	42.2	37.1
Equipment(miscellaneous)		19.2	14.4
TOTAL WTGP2	789.2	504.1	401.2
WTGP2 VOLUME CU. FT.	172,736	143,946	115,157
WTGP2 VOLUME REDUCTION %		16	33

spaces and the equipments contained within them.

By this method of measure, Group 2 volume was determined to be 172,736 cu.ft. The volume of the mechanical drive machinery removed, such as reduction gears, was subtracted from this value. The volume required for the superconducting electrical drive machinery was added to obtain the values of 143,946 cu.ft. and 115,157 cu.ft. for the four-engined and three-engined ships respectively, resulting in a propulsion plant space reduction of 16% for the four-engined ship and 33% for the three-engined ship. More space could be saved by a complete rearrangement of the machinery in each engine room, as the location of the propulsion gas turbines is no longer limited to one specific location by the restrictions of the reduction gear and propeller shaft. The result of a simple substitution of the superconducting electric generators for the reduction gears and shafting is shown in Figs. 5.1 and 5.2. The shortening of each engineroom by 8 feet, as shown in the machinery arrangement drawings, plus the addition of the two electric motor rooms(12x8x10 ft.) produces the 16% space reduction given in Table 5.3. The value of 115,157 cu.ft. for the three-engined ship was obtained in the same manner. A sample machinery space arrangement for the DD963 baseline and the DD963 electric drive ships is shown in Fig. 5.3.

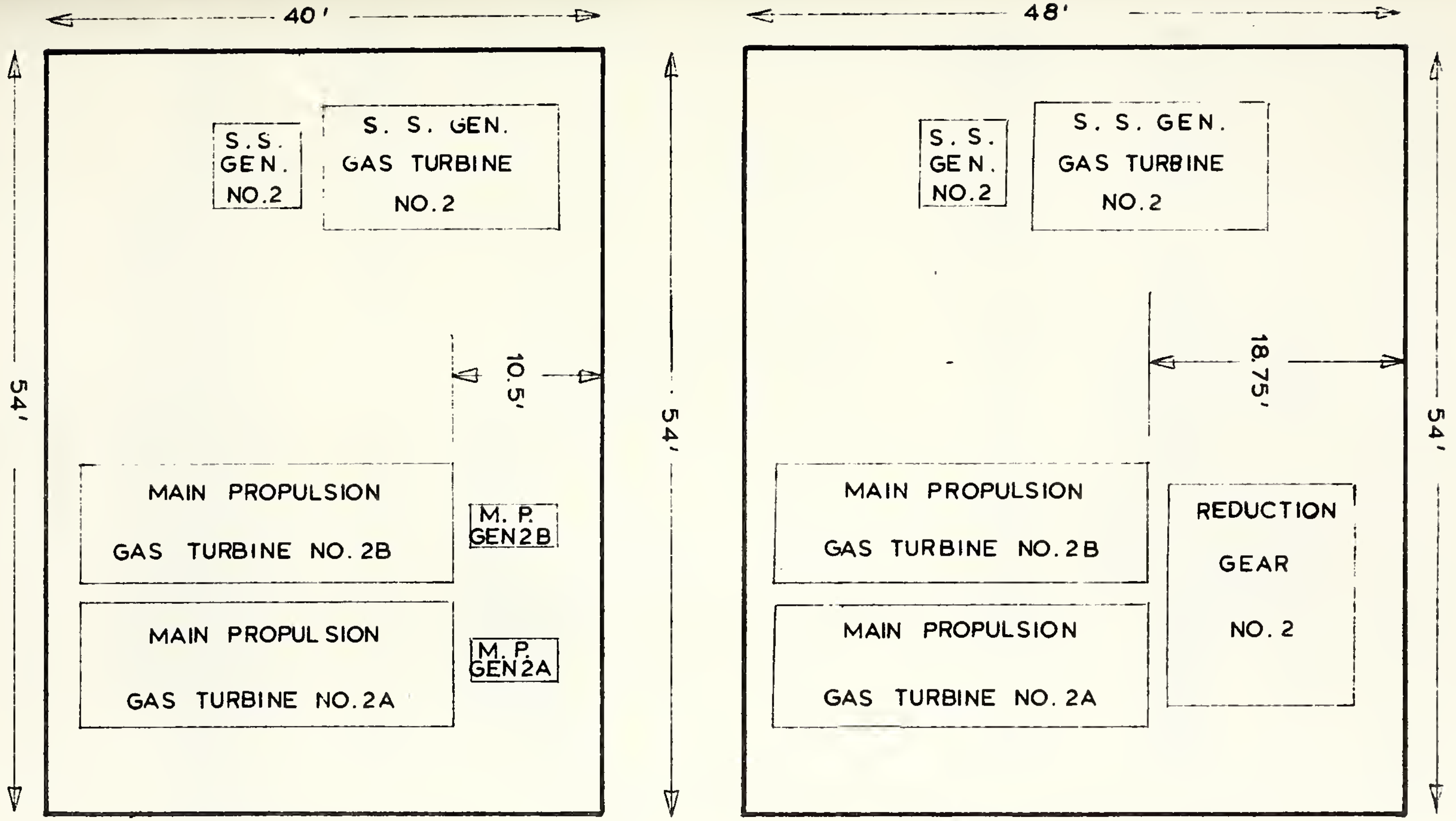


ENGINEROOM NO.1
ELECTRIC POWER PLANT

ENGINE ROOM NO.1
BASELINE POWER PLANT

ENGINEROOM NO.1 SIZE AND MACHINERY ARRANGEMENT FOR
BASELINE SHIP AND MODIFIED SHIP WITH SUPERCONDUCTIN ELECTRIC MACHINERY

Figure 5.1

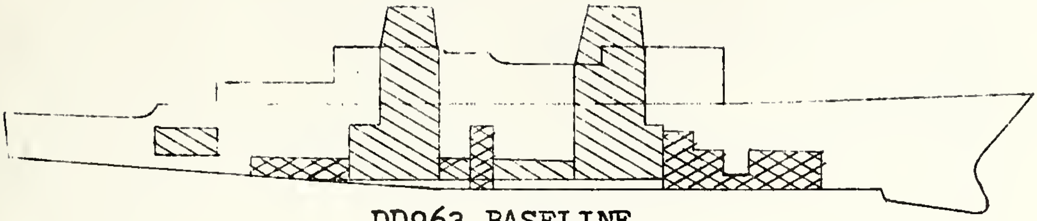

40'
54'
S.S. GEN. NO.2
S. S. GEN. GAS TURBINE NO.2
10.5'
MAIN PROPULSION GAS TURBINE NO. 2B
M. P. GEN 2B
MAIN PROPULSION GAS TURBINE NO. 2A
M. P. GEN 2A
54'
48'
S. S. GEN. NO.2
S. S. GEN. GAS TURBINE NO.2
18.75'
MAIN PROPULSION GAS TURBINE NO. 2B
MAIN PROPULSION GAS TURBINE NO. 2A
REDUCTION GEAR NO. 2
54'

ENGINE ROOM NO.2
ELECTRIC POWER PLANT

ENGINE ROOM NO.2
BASELINE POWER PLANT

ENGINE ROOM NO.2 SIZE AND MACHINERY ARRANGEMENT FOR BASELINE SHIP AND MODIFIED WITH SUPERCONDUCTING ELECTRIC MACHINERY

Figure 5.2

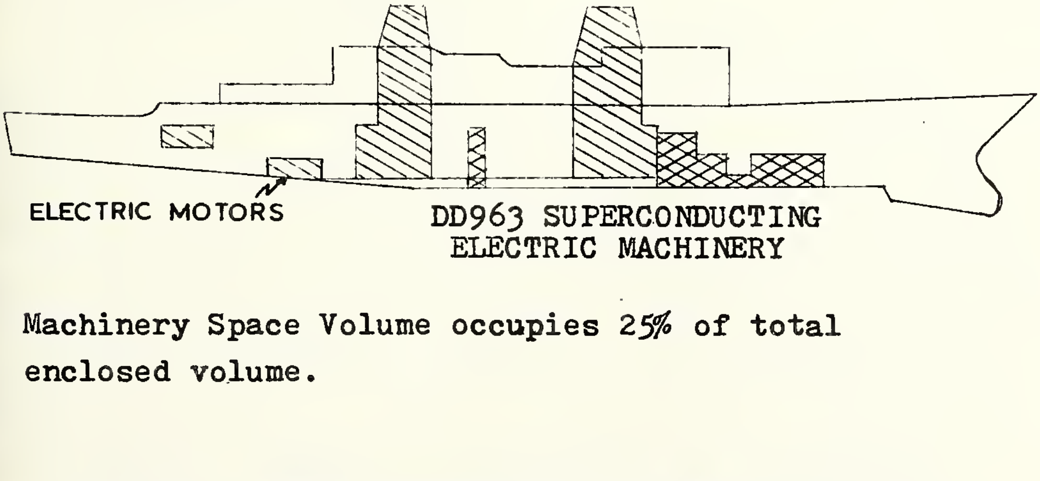


DD963 BASELINE

Machinery Space Volume occupies 30% of total enclosed volume.

▧ - Machinery and Uptakes

▩ - Fuel Storage



DD963 SUPERCONDUCTING
ELECTRIC MACHINERY

Machinery Space Volume occupies 25% of total enclosed volume.

MACHINERY SPACE ARRANGEMENTS FOR BASELINE SHIP AND ONE OF THE POSSIBLE ARRANGEMENTS FOR A SHIP MODIFIED TO ELECTRIC PROPULSION

Figure 5.3

5.3 Comparison of Baseline and Modified Ships

Machinery System weights and volumes derived in Section 5.2 for the electric propulsion system were used as input into the ship synthesis model. The calculated modified ship characteristics were compared to the baseline characteristics. The characteristics of the Model Baseline, Model Electric propulsion with four-engines and the Model Electric propulsion with three-engines are given in Table 5.4, with the same characteristics for the DD963 in Table 5.6. Tables 5.5 and 5.7 contain the weight and volume breakdown for the Model and DD963 ships based on a functional grouping of ship functions.

5.3.1 Analysis of Model Ships

When the baseline and the four-engine electric drive are compared, there are three major points of variance: the range, WTGP2, and the weight of WTGP2 in pounds divided by the shaft horsepower. The large difference in range can be attributed to the manner in which the two different plants are operated. For cruising at the endurance speed of 20 knots, the mechanical drive ship is required to operate two gas turbines, one for each shaft. The endurance shaft horsepower is 10,548 HP which works out to approximately 5300 HP per gas turbine. Fig.2.3 in Chapter 2 indicates that the specific fuel consumption (SFC) of two engines, each operating at 5300 HP, is

Table 5.4

CHARACTERISTICS OF MODEL BASELINE AND MODEL ELECTRIC PROPULSION SYSTEM SHIPS

	MODEL BASELINE	MODEL ELECTRIC 4 ENGINES	MODEL ELECTRIC 3 ENGINES
LBP	529	529	501.3
B	54.6	54.6	53.7
T	16.8	16.8	16.1
SHP INSTALLED	80000	80000	60000
SHP END	10548	10332	9491
V_{fp}	33.9	34.3	33.4
V_{end}	20.0	20.0	20.0
Range	6000	7874.3	6000
Displacement	6906	6657.4	5938.3
WTGP1	2465.2	2465.2	2181.8
WTGP2	789.2	504.1	401.2
WTGP3	282.7	282.7	265.2
WTGP4	207.4	207.4	207.4
WTGP5	569.1	569.1	561.3
WTGP6	499.8	499.8	480.8
WTGP7	159.2	159.2	159.2
Loads	1869.8	1869.8	1771.2
WT Margin	100.0	100.0	100.0
∇ Total	945470	945470	869832
WT PAY/Δ	.05	.05	.064
WT PERS/Δ	.04	.04	.04
WT OPS/Δ	.47	.44	.45
VOL PAY/∇	.12	.15	.13
VOL PERS/∇	.27	.27	.30
VOL OPS/∇	.62	.59	.58
WTGP2/SHP	22.1	14.1	15.0
VOL MACH BOX/SHP	2.45	2.16	2.49
VOL HAB/MAN	724	724	724
SHP/Δ	11.58	12.0	10.1
VOL MACH SYS/∇	.31	.28	.26
WTGP2/Δ	.11	.076	.068
VOL MACH BOX	195955	172675	149253
VOL UPTAKES	49150	48789	34973
VCL SHAFT.&BEAR.	3848	0	0

Table 5.5

FUNCTIONAL GROUP WEIGHTS AND VOLUMES OF MODEL BASELINE AND ELECTRIC PROPULSION SYSTEM

	MODEL BASELINE	MODEL ELECTRIC 4 ENGINES	MODEL ELETRIC 3 ENGINES
Vol. Hull	761020	761020	683734
Vol. Superstructure	184449	184449	168802
Vol. Total	945470	945470	852536
VOLUME			
Military Mission	110753	139038	110753
Personnel	251990	251990	251990
Control	56758	56758	52975
Mach. Sys.	293597	265312	221313
Deck Aux.	5194	5194	4662
Maintenance	18614	18614	17727
Stowage	69736	69736	58918
Tankage	21225	21225	19466
Pass & Access	117605	117605	114732
WEIGHT			
Military Mission	379.8	379.8	379.8
Personnel	247.8	247.8	247.8
Control	81.3	81.3	78.1
Mach. Sys.	1205.7	930.6	818.5
Deck Aux.	97.9	97.9	97.9
Maintenance	101.9	101.9	100.1
Stowage	1732.4	1732.4	1277.4
Pass & Access	14.9	14.9	14.2
Hull Group	2502.3	2502.3	2181.8
Ship Sys.	551.4	551.4	529.3

Table 5.6

CHARACTERISTICS OF DD963 BASELINE AND DD963 ELECTRIC PROPULSION SYSTEM SHIPS

	DD963 BASELINE	DD963 ELECTRIC 4 ENGINES	DD963 ELECTRIC 3 ENGINES
LBP	529	529	509.8
B	55.8	55.8	54.7
T	18.8	18.8	17.18
SHP INSTALLED	80000	80000	60000
SHP ENDURANCE	11483	11237	10418
V_{sus}	32.9	33.2	32.26
V_{end}	20	20	20
Range	6000	7848.1	6000
Displaement	7885.0	7568.4	6800.7
WTGP1	3137.1	3105.6	2757.7
WTGP2	789.2	504.1	401.2
WTGP3	296.8	296.8	275.9
WTGP4	250.3	250.3	250.3
WTGP5	739.8	739.8	735.5
WTGP6	454.3	454.3	445.9
WTGP7	159.2	159.2	159.2
Loads	1958.6	1958.6	1864.6
Wt. Margin	100	100	100
∇ Total	1013880	1013880	912864.9
WT PAY/Δ	.05	.05	.06
WT PERS/Δ	.03	.03	.035
WT OPS/Δ	.44	.41	.43
VOL PAY/∇	.16	.18	.17
VOL PERS/∇	.25	.25	.28
VOL OPS/∇	.59	.57	.55
WTGP2/SHP	22.1	14.1	15.0
VOL MACH BOX/SHP	2.45	2.16	2.49
VOL HAB/MAN	724	724	724
SHP/Δ	10.14	10.52	8.82
VOL MACH SYS/∇	.29	.26	.24
WTGP2/Δ	.10	.07	.060
VOL MACH BOX	195955	172675	149253
VOL UPTAKES	49150	48789	34973
VOL SHAFT & BEARINGS	3848	0	0

Table 5.7

FUNCTIONAL GROUP WEIGHTS AND VOLUMES OF DD963 BASELINE AND ELECTRIC PROPULSION SYSTEM

	DD963 BASELINE	DD963 ELECTRIC 4 ENGINES	DD963 ELECTRIC 3 ENGINES
Vol. Hull	772581	772581	707468
Vol. Superstructure	241298	241298	205396
Vol. Total	1013880	1013880	912865
VOLUME			
Military Mission	159298	186787	159298
Personnel	251990	251990	251990
Control	60633	60633	56912
Mach. Sys.	292801	265312	221013
Deck Aux.	5194	5194	4817
Maintenance	21330	21330	18003
Stowage	72459	72459	64573
Tankage	28171	28171	20808
Pass. & Access	122005	122005	115451
WEIGHT			
Military Mission	392.8	392.8	392.8
Personnel	238.8	238.8	238.8
Control	120.0	120.0	119.4
Mach. Sys.	1259.1	974.0	856.3
Deck Aux.	115.1	115.1	115.1
Maintenance	92.2	92.2	90.7
Stowage	1806.1	1806.1	1427.4
Tankage	0	0	0
Pass. & Access	13.5	13.5	12.8
Hull Group	3126.1	3126.1	2790.4
Ship Sys.	602.3	602.3	578.2

.64 lbs/hp-hr. The synthesis model calculated that for a mechanical drive ship with an SFC of .64 requires 1606 tons of fuel for an endurance range of 6000 nautical miles. At 6784 lbs/hr fuel consumed for 300 hours (time required to cover 6000 mi. at 20 knots) the ship would consume 908 tons of fuel with the remaining 698 tons of fuel being consumed to provide heat and electricity. Cruising at endurance speed requires only one gas turbine operating in an electric drive ship. Fig. 2.5 in Chapter 2 shows the SFC of one engine operating at 10,548 hp to be .5 lbs/hp-hr. When the specific fuel consumption drops to .5 lbs/hp-hr with an endurance SHP of 10,548 hp, it requires 393 hours to consume 908 tons of fuel.

Cruising for 393 hours at 20 knots produces an endurance range of 7874 nautical miles, which is considerably greater than the maximum required range of 6000 miles. The endurance range can be reduced to the desired 6000 miles by removing 202 tons of fuel for a 13% fuel reduction. This reduces the full load displacement to 6453 tons. For this displacement the ship is unstable due to the decreased draft. More weight would have to be added to make the ship stable again eliminating any advantages received from reducing the fuel weight. To produce a stable ship requires a reduction in the size of the hull, reducing the buoyancy and increasing the draft. A lighter

and smaller ship needs less power to provide the required full speed of 30+ knots; therefore, the primary reason for the three-engined propulsion plant ship. A smaller ship automatically implies less fuel (greatly reducing fuel weight) for the same endurance range. The smaller ship with an endurance horsepower of 9,491 and an SFC of .5 requires only 636 tons of propulsion fuel to cover 6000 nautical miles. This is approximately a 30% savings in propulsion fuel(a 17% fuel saving overall) for a ship that can perform identical functions at the same efficiency as the larger ship. The percent change from the baseline ship to the electric drive ships are shown in Table 5.8. Only those items which vary from the baseline values are listed. For example, the weight of armament does not change nor does the weight for Military Mission; therefore, they need not be listed in Table 5.8.

An examination of Table 5.8 indicates why the three-engined ship is preferred over the four-engined ship. The four-engined ship has large increases (20% or more) in range, volume, military mission and the payload volume fraction resulting in wasted space. The three-engined ship had a 20% increase only in the payload weight fraction indicating a more efficient ship design. The primary function of a Navy ship is to deliver as much military payload as possible where it is needed. Provided the

Table 5.8

CHANGE FROM MODEL BASELINE

PERCENT CHANGE FROM THE BASELINE TO ELECTRIC DRIVE, LISTING ONLY THOSE ITEMS WHICH CHANGE SIGNIGICANTLY FROM THE MODEL BASELINE SHIP

	4-ENGINE ELECTRIC % CHANGE*FROM BASELINE	3-ENGINE ELECTRIC % CHANGE*FROM BASELINE
LBP	0	5.2
SHP INSTALLED	0	25
V_{fp}	-1.2	1.5
Range	-31.2	0
Displacement	3.6	14.0
WTGP1	0	11.5
WTGP2	36.1	49.1
Volume Total	0	8
Volume Military Mission	-25.5	0
Volume Control	0	6.7
Volume Machinery System	9.63	24.6
Volume Stowage (Includes Fuel)	0	15.5
Volume Tankage	0	8.3
Weight Machinery System	22.8	32.1
Weight Stowage(Includes Fuel)	0	26.3
Weight Hull Group	0	12.8
Weight Payload/Displacement	0	-20.0
Weight Personnel/Displacement	0	0
Weight Operations/Displacement	6.4	4.2
Volume Payload/Volume Total	-25.0	-8.3
Volume Personnel/Volume Total	0	-11.1
Volume Operations/Volume Total	4.8	6.5
WTGP2/Shaft Horsepower	36.2	32.1
Volume Mach. Box/Shaft Horsepower	11.8	-1.6
Shaft Horsepower/Displacement	-3.6	12.8
Volume Mach. System/Volume Total	9.7	16.1
WTGP2/Displacement	30.9	38.2
Volume Machinery Box	11.9	23.9
Volume Uptakes	.7	28.8
Volume Shafting & Bearings	100	100
Full Load Ship Density lbs/cu.ft.	3.6	3.5

* (-) indicates an increase from the baseline

payload is the same and the ships have the same speed and endurance characteristics, a ship that has a payload which is 6% of its total weight is more efficient than one which has a payload of 5% of its total weight.

The overall summation of Table 5.8 is that a three-engined electric drive ship which is 14% lighter, 8% smaller, has a 24% smaller and 50% lighter propulsion system and carries 17% less fuel, can deliver an identical payload at the same speed and range as the larger and more expensive mechanical drive baseline ship.

5.3.2 Analysis of DD963 Ships

As for the four-engined model electric drive, the DD963 electric drive four-engined ship has a much greater range than the baseline ship. For this reason, the three-engined ship was synthesized to eliminate the excesses found in the four-engined ship. The DD963 three-engined electric drive ship also has a 20% increase in the payload weight fraction indicating a more efficient ship design.

The overall summary of Table 5.9 for the DD963 is a three-engined electric drive ship which is 14% lighter, 10% smaller, has a 25% smaller and 50% lighter propulsion system and carries 17% less fuel, can carry an identical payload at the same speed and range as the larger baseline ship.

5.4 Final Comparison of Model and DD963

Table 5.9

CHANGE FROM DD963 BASELINE

PERCENT CHANGE FROM THE BASELINE TO ELECTRIC DRIVE, LISTING ONLY THOSE ITEMS WHICH CHANGE SIGNIFICANTLY FROM THE DD963 BASELINE SHIP

	4-ENGINE ELECTRIC % CHANGE*FROM BASELINE	3-ENGINE ELECTRIC % CHANGE* FROM BASELINE
LBP	0	3.6
SHP INSTALLED	0	25
V_{fp}	-.9	1.9
Range	30.8	0
Displacement	4.0	13.8
WTGP1	1	11.2
WTGP2	36.1	49.1
Volume Total	0	9.9
Volume Military Mission	-17.3	0
Volume Control	0	6.1
Volume Machinery System	9.63	24.6
Volume Stowage(Includes Fuel)	0	10.8
Volume Tankage	0	5.4
Weight Machinery System	22.6	32.0
Weight Stowage(Includes Fuel)	0	21
Weight Hull Group	0	10.74
Weight Payload/Displacement	0	-20.0
Weight Personnel/Displacement	0	0
Weight Operations/Displacement	6.8	2.3
Volume Payload/Volume Total	-12.5	-6.3
Volume Personnel/Volume Total	0	-12.0
Volume Operations/Volume Total	3.4	6.8
WTGP2/Shaft Horsepower	36.2	32.1
Volume Mach. Box/Shaft Horsepower	11.8	-1.6
Shaft Horsepower/Displacement	-3.8	13.0
Volume Mach. System/Volume Total	10.3	17.2
WTGP2/Displacement	30.0	40.0
Volume Machinery Box	11.9	23.8
Volume Uptakes	.7	28.8
Volume Shafting & Bearings	100	100
Full Load Ship Density	4.0	1.5

*(-)indicates an increase from the baseline

The primary purpose of synthesizing both the superconducting powered Model and DD963 was to use the Model as a control case to check on the accuracy of the DD963 conclusions. The values associated with the model synthesis output can reasonably be assumed to be unbiased representations of actual changes brought about by the conversion to superconducting electric propulsion machinery. With the exception of the machinery box weight and volume, the Model weights and volumes for all ship functions are generated within accepted design lanes based on past design practices and philosophies. In the Model, there is no wasted or excess weight and volume which can be removed to provide a false indication of realized space and weight savings when conversion to electric propulsion is made. The DD963 is designed outside some of the accepted design lanes and consequently has excess volume which must be accounted for when analyzing the savings brought about by the conversion to superconducting electric machinery. The variation of each of these ships from their respective baseline ships is shown in Table 5.10. Those characteristics which are in disagreement are listed in the upper half of the table while the characteristics which agree are listed in the lower half.

The small percentage change in the full load ship density for the DD963 indicates that much of the excess

Table 5.10

CORRELATION OF MODEL AND DD963

PERCENT CHANGE OF 3-ENGINED MODEL AND 3-ENGINED DD963 FROM THEIR RESPECTIVE BASELINE SHIPS, SIGNIFICANT DIFFERENCES ONLY ARE LISTED

	MODEL % CHANGE*FROM BASELINE	DD963 % CHANGE*FROM BASELINE
CHARACTERISTICS WITH VARIANCE		
LBP	5.2	3.6
V_{fp}	1.5	1.9
Volume Total	8	9.9
Volume Stowage	15.5	10.8
Volume Tankage	8.3	5.4
Weight Stowage	26.3	21
Weight Hull Group	12.8	10.74
Weight Operations/Displacement	4.2	2.3
Volume Payload/Volume Total	-8.3	-6.3
Volume Mach. System/Volume Total	16.1	17.2
WTGP2/Displacement	38.2	40.0
Full Load Ship Density	3.5	1.5
CHARACTERISTICS WITHOUT VARIANCE		
Displacement	14.0	13.8
Volume Machinery System	24.6	24.6
Weight Mach. System/Displacement	32.1	31.9
Weight Payload/Displacement	-20.0	-20.0
Weight Personnel/Displacement	0	0
Volume Personnel/Total Volume	-11.1	-12.0
WTGP2/Shaft Horsepower	32.1	32.1
Volume Mach. Box/Shaft Horsepower	-1.6	-1.6
Shaft Horsepower/Displacement	12.8	13.0

* (-) indicates an increase from the baseline

volume had been removed during the synthesis process, the ship would have been much more dense. As it is, the density of the Model increased more than the density of the DD963. By comparing the changes in total volume, the DD963 only lost 2% more of its original baseline volume than did the Model. These two items considered together, would indicate that very little of the excess volume in the DD963 design was lost when the ship was converted to an electric propulsion system.

The smaller decrease in the volumes of stowage and tankage for the DD963 follows the conclusion that the DD963 is a less dense ship. These two volumes were greater to begin with, and when the volume for the fuel savings was removed it created a smaller percentage change than in the Model ship. Volume is also the cause for the full load displacement of the DD963 decreasing less than it did for the Model. The displacement of the DD963 is forced higher than it need be in order to have a hull large enough to enclose the required volume. If the volume were allowed to decrease more, the changes in full load displacement would be much closer.

Taking all of the above into consideration, the following conclusions can be drawn for powering a ship with superconducting electric machinery: When compared to a four-engined mechanical driven ship the three-engined

electrical drive ship will:

- be 9% smaller in volume
- be 14% lighter
- carry an identical payload
- have the same endurance and top speed
- have identical habitability standards
- have a 32% lighter machinery system
- have a 25% smaller machinery system
- use and carry approximately 17% less fuel
- have a 50% lighter propulsion system (WTGP2)
- have a 33% smaller propulsion system (WTGP2)

CHAPTER 6

Cost Analysis

6.1 Introduction

At this time, it would be very difficult to put a price on the acquisition and installation of a superconducting electric propulsion system. This thesis covers an economic comparison of how much such a propulsion system could cost and still be economically feasible. The cost of the mechanical drive machinery removed will be figured plus the difference in operating cost over the life of the ship. The operating costs of an electric drive ship are based on a 20 year life cycle, due to the fact the DD963 is designed on a life cycle of 20 years.

6.2 Cost of Removed Machinery

The single largest weight removed from the propulsion system is the shafting, bearings and propellers. 191.3 tons of shafting and bearings and 10.88 tons of propeller were removed. The cost of this removed weight can be assumed to be \$2000/ton,(17) which results in a \$404,360 cost savings. 32.4 tons of uptakes at \$1000/ton(17) were also removed for a cost reduction of \$32,400.

The reduction gears were the last large weight and volume pieces of machinery removed. The cost of the reduction gears is based on the total horsepower rating of the

gear and not on the weight of the machinery, as were the previous items. A representative cost of the reduction gears as installed in the DD963 can be based on a \$20/hp(18) figure. At \$20/hp, the cost of removing 80,000 shaft horsepower of reduction gears is \$1.6 million. The removal of the above mentioned equipments results in \$2 million savings.

6.3 Propulsion Plant Operating Costs

An operating profile of 30% underway time per year will be chosen as representative of this class of ship. While underway, 94% of the time will be at endurance speed and 6% of the time will be at full power. Underway fuel consumption will be calculated on a specific fuel consumption (SFC) of .42 lb/hp-hr while at full power. For the electric drive ship SFC at endurance speed is .5 lb/hp-hr, while for the mechanical drive endurance SFC is .64 lb/hp-hr. The SFC for the ships electrical power generation will be .96 lb/kw-hr(12) for an average 24 hour electric load of 1600 kw/hr(13). The price charged for fuel will be \$16.8/barrel(17) based on 1977 dollars and fuel prices. Total fuel costs per year are(19)

$$\text{Fuel Cost/Year} = \sum_i (\text{SFC}_i \times \text{SHP}_i \times \text{HOURS}_i/\text{YEAR} \times \text{FUEL COST/lb}) \tag{6.1}$$

Manning costs will be considered to be approximately

the same for both the electric drive and the mechanical drive ships. For a Navy ship, there should be the same number of men of equal pay grades and skills required for plant operation and maintenance. The difference in life cycle costs for the propulsion plants is calculated on acquisition costs and fuel costs.

6.3.1 Fuel Costs per Year

Fuel consumed per year is calculated by:[19]

$$\text{Fuel}_{(\text{CONS})} = (\text{SFC})\left(\frac{\text{days underway x 24hr/day x \%time at SFC}}{\text{2240 lb/ton}}\right)(\text{SHP})(\text{7.23 BBLS/TON}) \qquad (6.2)$$

The fuel consumed by the baseline ship is calculated first.

$$\text{Fuel(FULL POWER)} = \frac{(.42)(109 \text{ x } 24 \text{ x } .06)(80{,}000)}{2240}(7.23)$$

$$= 28{,}371 \text{ BBLS}$$

Fuel(ENDURANCE) = 52,920 BBLS

Fuel(ELECTRICAL) = 12,969 BBLS

Fuel Consumed/year = 99,670 BBLS

At $16.8/BBL, fuel cost for the baseline ship is $1,674,454.

The fuel consumed by the electric drive ship is:

$$\text{Fuel(FULL POWER)} = \frac{(.42)(109 \text{ x } 24 \text{ x } .06)(60{,}000)}{2240}(7.23)$$

Fuel (Full power)= 12,767 BBLS

Fuel (Endurance)= 41,344 BBLS

Fuel (Electrical) = 12,969 BBLS

Fuel Consumed/year = 67,080 BBLS

The total annual fuel cost for operating the elctric drive ship is \$1,126,944. The cost savings in fuel alone is \$547,510 per year.

6.3.2 P.V. of Life Cycle Plant Costs

To compute the present value (PV) of plant operating costs the discount rate (DR) is assumed to be 6% (based on real value 1977 dollars). The discount rate factor is:

$$C_{DR} = \left[\frac{(1 + DR)^{L} - 1}{DR(1 + DR)^{L}}\right] \qquad (6.3)$$

where L is the life of the ship. Present Value (PV) is

$$PV = \text{Cost/year } (C_{DR}) \qquad (6.4)$$

The present value of the fuel saved over the 20 years life of the ship is:

$$C_{DR} = 12.5$$

$$PV = \$547,510\ (12.5)$$

$$= \$6,843,875$$

The Present Value of \$6,8 million fuel cost savings

is valid only if the cost of fuel does not change over the next 20 years. One would have to be very naive to even assume that the cost of fuel will not continue to change. The $6.8 million fuel cost savings is a bottom-line figure based on the assumption that fuel costs will not rise any faster than will inflation. As the cost of fuel continues to rise, the fuel economical ship is even more desirable and the fuel savings for the electric drive ship continues going up.

6.4 Limit Cost of Electric Drive

The total cost of equipment removed plus the present value of 20 years fuel savings is 8.48 million. Using this value as a guideline, the superconducting electric propulsion machinery is economically feasible if the acquisition cost of threee generators, two motors, six cryogenic refrigerators, switch gear and cabling is $8.48 million or less.

For a 60,000 hp ship, this value breaks down to a cost of $141 per horsepower, or $188 per KW. $188 per KW for an upper limit cost of a complete superconducting electric propulsion system appears to be obtainable utilizing current superconducting technology.

The $ 8.48 million savings figure does not take into account the decreased acquisition cost or the yearly decrease in maintenance costs of a 10% smaller ship. The 20 year cost of paint alone will be a substantial savings.

Inclusion of these additional savings would only increase the upper limit acquisition cost of an electric transmission system.

CHAPTER 7

Conclusions and Recommendations

The results of the design criteria which were applied to a propulsion system incorporating superconducting electrical machines indicates that development of this technology will provide a significant reduction in machinery weight and volume. In any comprehensive study of competitive propulsion systems for a particular ship design, the superconducting electric system must be considered a viable candidate for increasing the overall ship performance.

The work associated with this thesis leads to some specific conclusions, resulting from the substitution of superconducting electric machines for the transmission system presently installed in the DD963 and the subsequent reduction in ship size and propulsion system size and power. Additionally some general conclusions can be drawn for the application of these machines in other propulsion systems. The specific conclusions can be enumerated:

1. A 388 LT reduction in machinery plant weight (50%), exclusive of fuel, can be realized by the substitution of the proposed system for the presently installed. A projection of gas turbine fuel consumption improvement allows fuel weight to be reduced by 272 LT for a 17% reduction.

When machinery and fuel weight savings are considered together, there is an absolute weight savings of 660 LT.

2. Substitution of the proposed system in the DD963 produced a marked improvement in the volume required for the machinery plant, for a volume reduction of 29,000 ft^3 (16%). This reduced volume would still allow sufficient space for the performance of machinery maintenance.

3. A smaller ship carrying an identical payload and having identical performance characteristics can be constructed to take full advantage of the weight and volume savings provided by the proposed propulsion system. The construction of the smaller three-engined ship versus the original four-engined ship, produced an overall weight reduction of 1085 LT for a 14% weight reduction and a 9% savings in volume.

4. A superconducting electric transmission system is economically feasible if its acquisition cost is $8.48 million or less ($141 per horsepower).

In addition to the above conclusions, some general observations about the proposed superconducting system are:

1. The use of an electric transmission system allows the efficient operation of gas turbines without the problem of excessive fuel consumption at off-design conditions. The power plant can be divided easily into several

generating units, each with a gas turbine and superconducting generator, without requiring the individual units being clustered around the reduction gears. Increased prime mover dispersion will decrease the vulnerablility of the propulsion plant. The number of economical operating speeds would correspond to the number of generating units.

2. Application of the proposed system in any particular ship design would not preclude any future changes in components that take advantage of technological improvements. All components of the proposed propulsion system are small enough that they could be replaced by an improved machine with relative ease. Substitution of original equipment with new and improved designs may be very desirable over the life of the ship.

3. The proposed electric drive system has a high degree of controllability, primarily due to the ability to use all electric controls for power control.

These conclusions demonstrate the desirability and the feasibility of incorporating superconducting electric machines in Naval ship propulsion systems.

This thesis has touched on several areas which require further investigation before superconducting electric machines can be used in marine applications. The most important of these is the actual details of machine construction. In addition to the specific machine design problems,

the use of solid state converters for the control of synchronous motors and the liquefier/refrigerator cryogenic system, as proposed here, will require further exploration and development. The poor controllability and torque characteristics of synchronous motors at low power levels and RPMs would probably necessitate the use of a conventional electric motor to start and power the propellers at low RPMs. This motor could be in the configuration of a motor around the propeller shaft driven by the ships service electrical power. Low speed maneuvering in restricted waters and emergency propulsion in the event of total failure of the superconducting machinery could be provided by these conventional motors.

A detailed engineering design study would have to be performed before the proposed propulsion system could be substituted for the original in the DD963. Propulsion plant machinery rearrangements should be made to prove the validity of the conclusions drawn in this thesis. Weight and moment calculations would be required to check the stability and trim of the modified vessel.

The preceding suggested areas of development and study are only those which are the most obvious at the conclusion of this thesis, and certainly many additional problem areas will have to be addressed for theory to be translated into reality.

APPENDIX A

Superconducting Machine Design Program

```
C$JOB
C**** SUPERCONDUCTING MACHINE DESIGN    ****
      DIMENSION V(8),HC(5),JC(5)
      DIMENSION VV(8),DV(8),VV1(8)
      DIMENSION DVL(8)
C           RFI,     TUF,    GFK,     THK,    GKA,     THA,    GAS,     AJF
      DATA V(1),    V(2),   V(3),    V(4),   V(5),    V(6),   V(7),    V(8)
     1/     .40,    .026,   .025,     .05,    .02,     .1 ,    .02,    1.2E+8 /
      DATA  DV(1),  DV(2), DV(3),   DV(4), DV(5),   DV(6), DV(7),   DV(8)
     1/     .04  ,  .0026, .0025,    .005,  .002,    .01,   .002,  1.2E+7 /
      DATA       DVL(1),    DVL(2),    DVL(3),    DVL(4)
     1/              .1,        .1,        .1,        .1    /
      DATA       DVL(5),    DVL(6),    DVL(7),    DVL(8),   TW
     1/              .1,        .1,        .1,        .1,   .1  /
      DATA       NUMIT
     1      / 15  /
      CFF=CF(V,NUMIT)
C**** STEPSIZE DETERMINITATION FOR OPTIMIZATION  ****
      EPSI=0.005
      NV=8
      CFO=CFF
      IF(NUMIT .EQ. 0) GO TO 100
      DO 2 NN=1,NUMIT
      DO 5 I=1,NV
      DO 1 II=1,NV
 1    VV(II)=V(II)
      Y1=CF(VV,NUMIT)
      A=.001*VV(I)
      IF(DV(I) .LT. A) DV(I)=VV(I)*.001
      VV(I)=VV(I)+DV(I)*TW
      Y2=CF(VV,NUMIT)
      VV(I)=VV(I)+DV(I)*TW
      Y3=CF(VV,NUMIT)
      IF(Y1+Y3-2.*Y2)50,50,53
 50   DX=-DV(I)*TW
      IF((Y1-Y2).LT.0.0) DX=DV(I)*TW
 52   IF((Y1-Y2).EQ.0.0) DX=0.0
      GO TO 54
 53   DX=DV(I)*(3.*Y1-4.*Y2+Y3)/(2.*Y1-4.*Y2+2.*Y3)*TW
 54   DV(I)=V(I)*DVL(I)
      IF(DX .LT. 0.0) DV(I)=V(I)*(-1.0)*DVL(I)
      IF(ABS(DX) .LT. (DVL(I)*V(I))) DV(I)=DX
 5    CONTINUE
      DO 3 KK=1,NV
 3    VV1(KK)=V(KK)+DV(KK)
      CF1=CF(VV1,NUMIT)
      WRITE (6,75)CF1,NN
      IF((CFO/CF1)-(1.0+EPSI))56,56,55
 55   DO 4 KK=1,NV
 4    V(KK)=VV1(KK)
      CFO=CF1
 2    CONTINUE
 56   NUMIT=0
      CFO=CF(V,NUMIT)
 75   FORMAT(' ',5X,15H COST FUNCTION ,5X,E10.4,10X,14H ITERATION NO.,
```

```
       15X,I6)
100     STOP
        END
```

```
      FUNCTION CF(V,NUM)
      DIMENSION V(8),HC(6),JC(6)
      DIMENSION H(20)
      REAL LZ, LCA, IA, IAS, LCA, ICK, LCF, LBB, NAAT, NFAT, LAK
      REAL IA, IF1, NA,  IN, MSS, MK, MS, MB, KGLOS, JSR, MA
      REAL  JC, 12, NPA, KWA, KBL, KBFL, LTH
      REAL KVAPU,NAPA,MU,KK
      REAL KBKL
      DATA      HC(1),    HC(2),    HC(3),    HC(4),    HC(5),   HC(6)
     1/         5.5E+6,   4.38E+6,  3.18E+6,  2.0E+6,   .796E+6,  0.0  /
      DATA      JC(1),    JC(2),    JC(3),    JC(4),    JC(5) ,  JC(6)
     1/          0.0,     1.0E+8,   2.0E+8,   3.0E+8,   4.0E+8, 4.6E+8 /
      DATA      VA,         PF,  PCIE,      RPM,       AJA
     1/     22.5E+6,      1.0,  6.0,      200.0,     3.5E+6   /
      DATA  THWAE,  THWFE, SFA, SFF, NPA, KWA, KBL,KBFL, LTH
     1/     1.047,  2.094,  .3,  .5,  3.,  1.,  1.,  .5, .25      /
      DATA  SIGMAA, SIGMAK,   KVAPU,  VT, XT, X1,  X2,  PR
     1/     6.0E+7, 2.0E+7,      1.,   1., .1, .1,  .1,  .3       /
      DATA ROSS,     E,      TMAX,  ROB,   GKI,  GAI, I2,   RP
     1/    8000., 2.0E+11, 4.5E+8, 1800., .02,  .02, .05, 1000. /
      DATA ROAL,     DMAX,      ROFE,      GAMMA
     1/    2600.,   2.4E+8,   7500.,      2.4      /
      DATA RCCU,    EAL
     1/   8800.,  6.94E+10  /
      DATA     BSMAX,    KBKL,      PZ
     1/        1.75,     1.0,      2.65      /
      RFI=V(1)
      THF=V(2)
      GFK=V(3)
      THK=V(4)
      GKA=V(5)
      THA=V(6)
      GAS=V(7)
      AJF=V(8)
      PI=3.14159
      MU=PI*4.0E-7
      PSI=ARCOS(PF)
      P=POIE/2.0
      OMEGA=RPM*P*2.0*PI/60.0
      HP=VA/746.0*PF
C**** CALCULATE MACHINE DIMENSIONS        ****
C**** RFO,RKO,RAO AREOUTER RADII OF FIELD, DAMPER, AND ARMATURE      ****
  499 RFO=RFI+THF
      RKI=RFO+GFK
      RKO=RKI+THK
      RAI=RKO+GKA
      RAO=RAI+THA
      RS=RAO+GAS
      X=RAI/RAO
      Y=RFI/RFO
      U=RKO/RS
      W=RAO/RS
      Z=RFO/RS
      ZZ=RKI/RKO
      RA=(RAO+RAI)/2.0
```

```
      RF=(RFO+RFI)/2.0
      RSB=(RKC+RKI)/2.0
      C10=THWAE/2.0
      C11=THWFE/2.0
      SC10=SIN(C10)
      SC11=SIN(C11)
      CM1=CM(P,X,W)
      CS1=CS(P,X,W)
      CC=2.0*P
      BB=2.0+P
      AA=2.0-P
C**** CALC LENGTH OF MACHINE            ****
C**** XIIS INTERNAL BASED REACTANCE     ****
      XI=(NPA*SQRT(2.)/4.)*(AJA/AJF)*(SC10/SC11)*((RAO/RFO)**BB)
     1*(CS1/(CM1*(1.0-Y**BB)))*KWA
C**** PPI IS KVA/UNIT LENGTH BASED ON INTERNAL VOLTAGE
      PPI=(8./(SQRT(2.)*PI))*OMEGA*MU*AJA*AJF*(1.0-Y**BB)*(RFO**BB)
     1*(RAO**AA)*CM1*SC10*SC11*KWA*NPA
C**** LZ IS UNIT LENGTH
      LZ=VA/PPI
C**** LDA IS EFFECTIVE LENGTH OF ARMATURE
      LDA=(RAO+RAI-(RFO+RFI)*KBPL)*KEL/P
      BETA=LDA/LZ
      AT=((XI**2*BETA)+XI*SIN(PSI))/(1.0-XI**2)
      ALPHA=AT+SQRT(AT**2+1.0+2.0*XI*BETA*SIN(PSI)+(XI*BETA)**2)
C**** LA IS ACTIVE ARMATURE LENGTH
      LA=LZ*ALPHA
C**** LAS IS ARMATURE STRAIGHT SECTION LENGTH
      LAS=LA-(RFO+RFI)*(KBPL)*KEL/P
C**** LOA IS TOTAL EFFECTIVE ARMATURE LENGTH
      LOA=LA+LDA
C**** XA IS TOTAL REACTANCE/UNIT BASED ON INTERNAL VOLTAGE
      XA=XI*(ICA/LA)
      IF(XA .LT. 1.0) GO TO 500
      THA=THA-THA*0.1
      GO TO 499
  500 VOE=SQRT(1.0-(XA*COS(PSI))**2)-XA*SIN(PSI)
      XD=XA/VOE
C**** LOK AND LOF ARE THE EFFECTIVE LENGTH OF DAMPER AND FIELD
      LOK=LA+(RKI+RKO)*(KBL/P)
      LOF=LA+(RFI+RFO)/P
C**** RULE OF THUMB GUESS FOR LENGTH OF BEARING SPAN
      LBR=LCK+2.0*LTH
C**** NAAT IS TOTAL NUMBER OF ARMATURE AMPERE-TURNS
      NAAT=AJA*THWAE*RAO**2*(1.0-X**2)/2.0
C**** NFAT IS TOTAL NUMBER OF FIELD AMPERE-TURNS
      NFAT=AJF*THWFE*RFO**2*(1.0-Y**2)/2.0
C**** VPT IS GENERATED VOLTAGE/TURN/PHASE
      VPT=32.0/(2.0*SQRT(2.0)*PI)*OMEGA*MU*LA*AJF*SC10*SC11
     1*(1.0-Y**BB)/(  THWAE*(1.0-X**2)*RAO**B)*RFO**BB*CM1*KWA*VOE
C
C**** CALC OF TRANSIENT ELECTRICAL PARAMETERS
C**** LAK IS ACTIVE ARMATURE LENGTH FOR COUPLING TO DAMPER
      LAK=LAS+(RKO+RKI)*KWA*KBKL/P
C**** XDP AND XDPP ARE TRANSIENT AND SUBTRANSIENT REACTANCES
```

```
      XDP=XD*(1.0-4.0*(LA**2*KWA/(LCA*LOF))*(CM(P,X,W)**2)/(CS(P,X,W)
     1*CS(P,Y,Z))*(RFO/RAO)**CC*(1.0-Y**BB)**2)
      XDPP=XD*(1.0-2.0*((LA**2)/(LCA*LCK))*(CM1**2)/(CS(P,X,W)
     1*CS(P,ZZ,U))*((RKO/RAO)**CC)*(1.0-ZZ**BB)**2)
C**** TS AND TDPP ARE SHIELD AND SUBTRANSIENT TIME CONSTANTS
      TS=PI*MU*RKC*(RKC-RKI)*SIGMAK/4.0*(1.0+ZZ)**CC
C**** TA IS ARMATURE TIME CONSTANT
      TA=2.0*MU*SC10**2*SIGMAA*SPA*RAO**2*CS(P,X,W)/
     1(PI*THWAF*(1.0-X**2))*NPA*KWA**2*XDPP/XD
      TDPP=TS*(XDP-XDPP)/(XD-XDPP)
C
C****FIELD CURRENT RISE
C     FIELD CURRENT RISE DURING CRITICAL POST-FAULT SWING
C     XE IS EXTERNAL REACTANCE
C     EFO AND VINF ARE INTERNAL AND BUS VOLTAGES
C     IF1 IS PER UNIT MAX FIELD CURRENT
      IA=KVAPU/VT
      XE=X1*X2/(X1+X2)+XT
      EFO=SQRT(VT**2+(XD*IA)**2+2.0*VT*XD*IA*SIN(PSI))
      VINF=SQRT(VT**2+(XE*IA)**2-2.0*VT*XE*IA*SIN(PSI))
      DEO=ARSIN(KVAPU*COS(PSI)*XE/(VINF*EFO))
      IF1=2.0*(XD-XDP)*COS(DEO)/(XDP+XE)/(EFO)+1.0
C
C**** TORQUE TUBE REQUIREMENTS
C     TORQUE TUBE IS DESIGNED TO CARRY WORST CASE TORQUE FROM
C     A LINE-LINE TERMINAL FAULT
C     TPP IS PER UNIT WORST CASE TORQUE
C     TT IS WORST CASE TORQUE
C     SQ IS RADIUS RATIO OF TORQUE TUBE.  THIS ROUTINE ATTEMPTS TO FIND
C     THE PROPER VALUE FOR SQ
      N=0
      IA=KVAPU/VT
      EPP=SQRT(VT**2+(XDPP*IA)**2+2.0*VT*XDPP*IA*SIN(PSI))
      TPP=1.3*EPP**2/XDPP
      TT=VA*TPP/OMEGA
C**** FINDING OPTIMUM INNER RADIUS
      SS=((3.0+PR)/16.0)*ROSS*RFI**2*OMEGA**2
      PR=0.5
      SQ=0.9
      SQNEW=0.0
C**** WILL TRY 250 TIMES FOR A SOLUTION
C     IF AFTER THAT MANY TRIES IT HAS NOT FOUND A SOLUTION
C     IT ESTIMATES STRESS FOR AN ALMOST SOLID SHAFT
 1210 IF(N.LT.250)GO TO 1220
      SI=2.0*SS
      SO=SI*(1.0-PR)/(3.0+PR)
      TAUO=2.0*TT/(PI*RFI**3)
      TO=SQRT(TAUO**2+SQ**2)
      TD=SI
      IF(TO .GT. SI) TD=TO
      RFI=0.0
      GO TO 1300
C**** REJECT NEGATIVE INNER RADIUS
C     AND INNER RADIUS GREATER THAN OUTER RADIUS
 1220 IF(SQNEW+SQ .LT. 0.0) SQNEW=SQNEW/2.0
```

```
      IF(SQNEW+SQ .GT. .99) SQNEW=SQNEW/2.0
      SQ=SQ+SQNEW
C**** SO,SI ARE HALF OF CENTRIFUGAL STRESSES AT OUTER,INNER RADII
      SO=SS*(2.0*(1.0-PR)/(3.0+PR)+2.0*SQ**2)
      SI=SS*(2.0*(1.0-PR)/(3.0+PR)*SQ**2+2.)
C**** TAUO AND TAUI ARE TORQUE STRESSES
      TAUO=2.0*TT/(RFI**3*(1.0-SQ**4)*PI)
      TAUI=2.0*SQ*TT/(RFI**3*(1.0-SQ**4)*PI)
C**** TO AND TI ARE MOHR'S CIRCLE ADDITIONS
      TO=SQRT(TAUO**2+SO**2)
      TI=SQRT(TAUI**2+SI**2)
C**** LARGER STRESS POINT USED AS CRITERION
      T1=TI
      IF(TO .GE. TI) T1=TO
C**** ATTEMPT TO GET WITHIN 95% OF SPECIFIED STRESS, TMAX
      IF(TMAX .LT. T1 .AND. .95*TMAX .GT. T1) GO TO 1230
C**** RBI IS SUPPORT INNER RADIUS
      RBI=SQ*RFI
C**** TD IS THE STRESS LEVEL USED TO CALCULATE SHAFT STRESS
C     PENALTY FUNCTION
      TD=TMAX
      GO TO 1300
C**** NEWTONS METHOD IS USED TO OBTAIN A NEW GUESS FOR SQ
C     DT1 IS RATE OF CHANGE OF STRESS WITH SQ
C     DS AND DT ARE COMPONENT DERIVATIVES
C     SQNEW IS THE ESTIMATE FOR THE CHANGE IN SQ REQUIRED
 1230 IF(TI-TO)1240,1250,1250
 1250 N=N+1
      DS=8.0*SQ*SS*(1.0+PR)/(3.0+PR)
      DTO=TAUO*4.0*SQ**3/(1.0-SQ**4)
      DT=TAUO+DTO
      DT1=(SI*DS+TAUI*DT)/T1
      SQNEW=PR*(.975*TMAX-T1)/DT1
      GO TO 1210
 1240 N=N+1
      DS=4.0*SQ*SS
      DT=TAUO*4.0*SQ**3/(1.0-SQ**4)
      DT1=(SO*DS+TAUO*DT)/T1
      SQNEW=PR*(.975*TMAX-T1)/DT1
      GO TO 1210
C**** DAMPER REQUIREMENTS FOR FAULT CRUSHING LOADS
C     DAMPER IS DESIGNED TO CARRY WORST CASE CRUSHING LOADS
C     FROM A LINE-LINE TERMINAL FAULT
C     STMG IS MAGNETIC STRESS AT SHORT CIRCUIT
C     STR IS TOTAL STRESS FROM A FAULT
C     STCF IS CENTRIFUGAL STRESS AT RATED SPEED
C     DFCF IS CENTRIFUGAL DEFLECTION AT RATED SPEED
C     DFMG IS MAGNETIC DEFLECTION FROM A FAULT
C     DFR IS TOTAL DEFLECTION AT SHORT CIRCUIT
 1300 RT=(RFI+RBI)/2.0
      THSB=RKO-RKI
      WWW=RT/RS
      ZZZ=RSF/RS
      CNTH=ABS(PF)
      SNTH=SQRT(1.0-PF*PF)*PF/CNTH
```

```
      SNDL=XA*CNTH
      CNDL=SQRT(1.0-SNDL*SNDL)
      BAO=4.242*MU/PI*SC10*BAO*(1.0-X+(1.0-X**3)/3.0*W**2)*AJA
      ELSS=PI*MU*(1.0+(RSB/RS)**2)/8.0
      NA=NAAT/AJA
      ELA=((16.0*LOA*MU*(NA**2)*(SC10**2))/(P*PI*(SC10**2)
     1*(1.0-X**2)**2))*SS*KWA**2
      ELS=ELA*1.5
      EMAP=2.0*MU*SC10*(PP/RAO)*(1.0-X+1.0/3.0*(1.0-X**3)*(RAO/RS)**2)
     1/(THWAE*(1.0-X**2))
      EMAS=EMAP*(RSB/RI)
      XD11=XD*(1.0-1.5*EMAS*EMAS/ELS/ELSS*LA/LOA)
      BA1=BAO/XD11
      BFO=0.66667*MU/PI*SC11*RSB*(RFO/RSB)**3*(1.0-Y**3)*(1.0-ZZZ**2)
     1*AJF
      DELT=ATAN(SNDL/CNDL)
      THET=ATAN(SNTH/CNTH)
      CCC=2.0*BA1/(1.0+ZZZ**2)
      AAA=BAO*SNTH+CCC+BFO*CNDL
      BBB=BAO*CNTH+BFO*SNDL
      BOT=SQRT(AAA**2+BBB**2+CCC)
      ATBA=ATAN(BBB/AAA)
      EEE=BFO*COS(ATBA-DELT)+BAO*SIN(ATBA+THET)
      DDD=BFO*SIN(ATBA-DELT)-BAO*COS(ATBA+THET)
      FR1=(BOT**2-EEE**2-DDD**2)/MU/4.0E4
      FR2=SQRT((BOT**2-EEE**2+DDD**2)**2+(EEE*DDD)**2)
     1*4.0/MU/4.0E4
C**** FR IS MAX RADIAL FORCE AT FAULT
      FR=FR1+FR2
      STMB=FR2*2.0*RSB**2/THSB/TBSB
      STMU=-FR1*RSB/THSB
      STMG=STMB-STMU
      VLB=RKO**2-RKI**2
      RHSB=VLB*ROAL
      STCF=RHSB*RSB**2*OMEGA**2*1.0E-4
      STB=STMB+STCF+STMU
      AIS=RKO**4-RKI**4
      ESB=EAL*AIS
      DFMB=2.0/3.0*FR2*2.0E4/ESB/THSB**3*RSB**4
      DFMU=STMU*RSB/ESB*1.0E4
      DFMG=DFMB-DFMU
      DFCF=STCF*RSB/ESB*1.0E4
      DFB=DFMB+DFCF+DFMU
C
C**** NEGATIVE SEQUENCE LOSSES
C     KK IS SHIELD CURRENT DENSITY
      KK=4.0*AJA*I2*SC10*RKO**(P-1.0)*RAO**(2.0-P)*P*BB*CM(P,X,W)/
     1(PI*(1.0+U**CC))
      DDS=SQRT(2.0/(OMEGA*MU*SIGMAK))
      PSH=(KK**2*PI*RKO*LOK)/(       SIGMAK*DDS)
C
C**** ARMATURE LOSSES
      PA=(AJA**2/(SIGMAA*SFA))*THWAE*RAO**2*(1.0-X**2)*LOA*NPA
C
C**** FIELD AT SHIELD RADIUS
```

```
      BRS=MU*((4.0*AJF*SC11)/(BB*PI))*RS*Z**BB*(1.0-Y**BB)
C     RSO IS SHIELD OUTER RADIUS
C     SHIELD IS DESIGNED FOR UNIFORM FLUX DENSITY
      RSO=RS*(1.0+BRS/(BSMAX*P))
C
C**** FIELD AT AN INNER CORNER OF FIELD WINDING
      HR=0
      HTH=0
C     ESTIMATE FIELD INTENSITY AT INNER RADIUS AND HIGHEST ANGULAR
C     EXTENT OF THE FIELD WINDING.  HARMONICS 1 TO 19 AND BOTH RADIAL AND
C     AZIMUTHAL COMPONENTS ARE INCLUDED.
      DO 1500 I=1,20,2
      F=FLOAT(I)*P
      G=FLOAT(I)*THWFE/2.0
 1500 H(I)=2.0*AJF*SIN(G)/(FLOAT(I)*PI*(2.0-F))*RFI*Y**(F-2.0)
     1*CM(F,Y,Z)*(4.0-F**2)*F
      DO 1600K=1,20,2
      EE=FLOAT(K)*THWFE/2.0
      HR=HR+H(K)*SIN(EE)
 1600 HTH=HTH+H(K)*COS(EE)
      BMAX=SQRT(HR**2+HTH**2)
C
C**** ROTOR CRITICAL SPEED
C     COMPUTE ROTOR CRITICAL SPEED USING A SIMPLE BENDING MOMENT MODEL
C     TORQUE TUBE STIFFNESS ONLY IS USED
C     MASS MA INCLUDES TORQUE TUBE, SHIELD, AND FIELD
      MA=(ROSS*(RFI**2-RBI**2)+RCCU*SEF*RFC**2*(1.0-Y**2)
     1+ROAL*(RKO**2-RKI**2))*PI+ROB*((RFO+GFK-GKI)**2-RFO**2)*PI
C     IN IS TORQUE TUBE MOMENT OF INERTIA
      IN=(3.1416/4.0)*(RFI**4-RBI**4)
      OMGCRT=9.875*SQRT(E*IN/(LBR**4*MA))
      OMRPM=OMGCRT/(2.0*PI)*60.0
C
C**** WEIGHTS OF MAJOR MATERIALS
C     STAINLESS STEEL(TORQUE TUBE), COPPER(ARMATURE), STEEL(IRON SHIELD)
C     AND ALUMINUM(DAMPER)
      MSS=PI*(RFI**2-RBI**2)*LBF*ROSS
      MK=PI*RKO**2*(1.0-ZZ**2)*LCK*RCAL
      MA=PI*RAO**2*(1.0-X**2)*LOA*ROCU*SPA
      MS=PI*(RSO**2-RS**2)*LCA*RCFE
C     MB IS WEIGHT OF BINDING MATERIAL
      MB=PI*((RFO+GFK-GKI)**2-RFC**2)*LOF
C
C**** SUPERCONDUCTIOR REQUIREMENTS FOR COST ESTIMATES
C     RESULT IS IN AMPERE-TURNS-METERS
      ATM=(AJF*THWFE*RFO**2*(1.0-Y**2)/2.0)*2.0*LOF
C
C**** STATOR CORE LOSSES
C     PPKG IS CORE LOSS DENSITY IN WATTS/KG
      PPKG=PZ*(BRS/BSMAX)**GAMMA
      PCORE=MS*PPKG
C
C**** COST FUNCTION
C     C IS COST OF MACHINE IN WEIGHT
      C=MSS+MA+MK+MS+MB
```

```
      ALOS=PA+PCORE+PSH
C     WLOS IS IN KG PER WATT
      WLOS=C/ALOS
      WATLOS=ALOS
      KGLOS=WLOS*ALOS
      PFLS=1.0
C
C**** PENALTY FUNCTION FOR FIELD CURRENT LIMIT
C     FIELD CHARACTERISTICS ARE INPUT AS FIVE POINTS IN H-J PLANES
C     H IS IN HC ARRAY, J IS IN JC ARRAY
C     H IS ASSUMED CONSTANT IN A SWING
C     FOR A FIXED H, LINEAR INTERPOLATION IS USED TO OBTAIN CRITICAL
C     CURRENT DENSITY
C     HMAX IS MAXIMUM FIELD INTENSITY
      IF(HMAX .LE. HC(1)) GO TO 10
      PPFC=10**40
      GO TO 11
 10   DO 1700 I=2,5
      K=I-1
      L=I+1
      IF(HMAX .GT. HC(I) .AND. HMAX .LE. HC(K))
     1JSR=JC(I)+(JC(L)-JC(I))*(HMAX-HC(I))/(HC(L)-HC(I))
 1700 CONTINUE
      IF(HMAX .LT. HC(5)) JSR=JC(5)
      PPFC=.9+.1*(AJF*IF1/JSR)**15
C
C**** PENALTY FUNCTION FOR SHAFT STRESS
 11   PPSI=.9+.1*(TD/TMAX)**15
C
C**** PENALTY FUNCTION FOR SHAFT CRITICAL SPEED
C     PROVISION IS MADE TO FORCE LOW CRITICA SPEED AND TO KEEP
C     CRITICAL SPEED AWAY FROM OPERATIN SPEED
      PFCS=.9+.1*(OMEGA/(P*OMGCRT))**3+.001*(P*OMGCRT/(P*OMGCRT-
     1OMEGA))**2
C
C**** PENALTY FUNCTION FOR SHIELD FLUX LIMIT
      PPSF=.9+.1*(BRS/BSMAX)**15
C
C**** PENALTY FUNCTION FOR DAMPER STRESS
      PFDS=.9+.1*(STB/DMAX)**5
C
C**** PENALTY FUNCTION FOR ARMATURE INSULATION AND DIAMETER
      PPAI=.9+.1*(GAI/(RAI-RKO))**15
      PPAC=.9+.1*(GAI/(RS-RAC))**15
C
C**** FINAL COST FUNCTION
      CF=C*PPSI*PFCS*PPSF*PPFC*PFDS*PPLS*PPAI*PPAC
      IF (NUM .GT. 0) GO TO 100
      V11=VA/1E06
      V12=HMAX*MU
      WRITE(6,701)
      WRITE(6,703)
      WRITE(6,705)
      WRITE(6,707) HP
      WRITE(6,709) V11
```

```
      WRITE(6,711)  PF
      WRITE(6,713)  RPM
      WRITE(6,715)  P
      WRITE(6,717)  VT
      WRITE(6,718)  AJA
      WRITE(6,719)  KVAED
      WRITE(6,703)
      WRITE(6,721)
      WRITE(6,723)  V(6)
      WRITE(6,725)  V(7)
      WRITE(6,727)  RAO
      WRITE(6,729)  LCA
      WRITE(6,731)  LA
      WRITE(6,733)  LAS
      WRITE(6,735)  VFT
      WRITE(6,737)  NAAT
      WRITE(6,739)  SFA
      WRITE(6,741)  NPA
      WRITE(6,743)  SIGMAA
      WRITE(6,745)  THWAE
      WRITE(6,703)
      WRITE(6,751)
      WRITE(6,753)  V(2)
      WRITE(6,755)  V(1)
      WRITE(6,757)  V(3)
      WRITE(6,759)  LA
      WRITE(6,761)  LCF
      WRITE(6,763)  AJF
      WRITE(6,765)  SFF
      WRITE(6,767)  THWFE
      WRITE(6,769)  NEAT
      WRITE(6,771)  IF1
      WRITE(6,773)  V12
      WRITE(6,775)  XD
      WRITE(6,777)  XDP
      WRITE(6,779)  XDPP
      WRITE(6,703)
      WRITE(6,781)
      WRITE(6,783)  V(4)
      WRITE(6,785)  RKO
      WRITE(6,787)  V(5)
      WRITE(6,789)  LCK
      WRITE(6,791)  LAK
      WRITE(6,793)  SIGMAK
      WRITE(6,703)
      WRITE(6,796)
      WRITE(6,797)  XT
      WRITE(6,798)  X1
      WRITE(6,799)  X2
      WRITE(6,703)
      WRITE(6,801)
      WRITE(6,803)  OMGCRT
      WRITE(6,805)  LPR
      WRITE(6,703)
      WRITE(6,811)
```

```
      WRITE(6,813) MSS
      WRITE(6,815) MK
      WRITE(6,817) MA
      WRITE(6,819) MB
      WRITE(6,821) MS
      WRITE(6,703)
      WRITE(6,831)
      WRITE(6,833) BFS
      WRITE(6,835) RSO
      WRITE(6,837) RS
      WRITE(6,839) BSMAX
      WRITE(6,703)
      WRITE(6,841)
      WRITE(6,843) PA
      WRITE(6,845) PCORE
      WRITE(6,847) PSH
      WRITE(6,849) WATLOS
      WRITE(6,851) WLOS
      WRITE(6,853) KGLOS
      WRITE(6,703)
      WRITE(6,871)
      WRITE(6,873) RCCU
      WRITE(6,875) RCFE
      WRITE(6,877) RCAL
      WRITE(6,879) ROSS
      WRITE(6,880) RCB
      WRITE(6,703)
      WRITE(6,881)
      WRITE(6,883) PFSI
      WRITE(6,885) PFCS
      WRITE(6,887) PFSP
      WRITE(6,889) PFFC
      WRITE(6,891) PFDS
      WRITE(6,890) PFAI
      WRITE(6,892) PFAC
      WRITE(6,703)
      WRITE(6,901)
      WRITE(6,905) C
      WRITE(6,907) CF
      WRITE(6,703)
      WRITE(6,911)
      WRITE(6,913) DMAX
      WRITE(6,915) TMAX
      WRITE(6,917) E
      WRITE(6,919) PR
      WRITE(6,703)
      WRITE (6,5000)
  701 FORMAT(1H1,10X,40H SUPERCONDUCTING GENERATOR/MOTOR DESIGN )
  703 FORMAT(/72H-------------------------------------------------------
     1-----------------/)
  705 FORMAT(13H ** RATING **)
  707 FORMAT(5X,46H RATED POWER (HP)............................,F10.0)
  709 FORMAT(5X,46H RATED POWER (MVA)...........................,F10.0)
  711 FORMAT(5X,46H POWER FACTOR ...............................,F10.3)
  713 FORMAT(5X,46H MECHANICAL SPEED (RPM)......................,F10.0)
```

```
  715 FORMAT(5X,46H NUMBER OF POLE PAIRS .........................,F10.0)
  717 FORMAT(5X,46H TERMINAL VOLTAGE (V)..........................,F10.0)
 718  FORMAT(5X,46H ARMATURE CURRENT (A)..........................,E10.4)
 719  FORMAT(5X,46H PER UNIT POWER RATING (P.U.)..................,F10.2)
 721  FORMAT(15H ** ARMATURE **)
 723  FORMAT(5X,46H ARMATURE THICKNESS (M)........................,F10.4)
 725  FORMAT(5X,46H ARMATURE TO CORE GAP (M) .....................,F10.4)
 727  FORMAT(5X,46H ARMATURE OUTER RADIUS (M).....................,F10.4)
 729  FORMAT(5X,46H AVER ALL ARMATURE LENGTH (M) .................,F10.4)
 731  FORMAT(5X,46H ACTIVE ARMATURE LENGTH (M)....................,F10.4)
 733  FORMAT(5X,46H STRAIGHT SECTION LENGTH (M)...................,F10.4)
 735  FORMAT(5X,46H VOLT PER TURN (RMS)...........................,F10.5)
 737  FORMAT(5X,46H ARMATURE AMPERE-TURNS (RMS/PHASE).............,E10.4)
 739  FORMAT(5X,46H ARMATURE WINDING SPACE FACTOR ................,F10.4)
 741  FORMAT(5X,46H NO. OF ARMATURE PHASES .......................,F10.4)
 743  FORMAT(5X,46H ARMATURE CONDUCTIVITY (S/M) ..................,E10.4)
 745  FORMAT(5X,46H ARMATURE ANGLE (RAD) .........................,F10.4)
 751  FORMAT(20H ** FIELD WINDING **)
 753  FORMAT(5X,46H FIELD THICKNESS (M) ..........................,F10.4)
 755  FORMAT(5X,46H FIELD INNER RADIUS (M)........................,F10.4)
 757  FORMAT(5X,46H FIELD TO DAMPER GAP (M) ......................,F10.4)
 759  FORMAT(5X,46H ACTIVE MACHINE LENGTH (M) ....................,F10.4)
 761  FORMAT(5X,46H OVERALL FIELD LENGTH (M) .....................,F10.4)
 763  FORMAT(5X,46H FIELD CURRENT DENSITY (A/M**2) ...............,E10.4)
 765  FORMAT(5X,46H FIELD WINDING SPACE FACTOR ...................,F10.4)
 767  FORMAT(5X,46H FIELD ELECTRICAL WINDING ANGLE (RAD) .........,F10.4)
 769  FORMAT(5X,46H FIELD AMPERE-TURNS (A-T) .....................,E10.4)
 771  FORMAT(5X,46H MAX PER UNIT FIELD CURRENT (P.U.).............,F10.2)
 773  FORMAT(5X,46H MAXIMUM FIELD (TESLA) ........................,F10.0)
 775  FORMAT(5X,46H SYNCHRONOUS REACTANCE ........................,F10.4)
 777  FORMAT(5X,46H TRANSIENT REACTANCE ..........................,F10.4)
 779  FORMAT(5X,46H SUBTRANSIENT REACTANCE .......................,F10.4)
 781  FORMAT(13H ** DAMPER **)
 783  FORMAT(5X,46H DAMPER THICKNESS (M) .........................,F10.4)
 785  FORMAT(5X,46H DAMPER OUTER RADIUS (M) ......................,F10.4)
 787  FORMAT(5X,46H DAMPER TO ARMATURE GAP (M) ...................,F10.4)
 789  FORMAT(5X,46H OVERALL DAMPER LENGTH (M) ....................,F10.4)
 791  FORMAT(5X,46H ARMATURE COUPLING LENGTH (M) .................,F10.4)
 793  FORMAT(5X,46H DAMPER CONDUCTIVITY ..........................,E10.4)
 796  FORMAT(16H ** STABILITY **)
 797  FORMAT(5X,46H TRANSFORMER REACTANCE ........................,F10.4)
 798  FORMAT(5X,46H REACTANCE UNFAULTED LINE .....................,F10.4)
 799  FORMAT(5X,46H READTANCE FAULTED LINE .......................,F10.4)
 801  FORMAT(24H ** NATURAL FREQUENCY **)
 803  FORMAT(5X,46H ROTOR CRITICAL SPEED (RPM) ...................,F10.1)
 805  FORMAT(5X,46H BEARING SPAN (M) .............................,F10.4)
 811  FORMAT(13H ** WEIGHT **)
 813  FORMAT(5X,46H STAINLESS STEEL SUPPORT (KG) .................,F10.4)
 815  FORMAT(5X,46H SHIELD WINDING (KG) ..........................,F10.4)
 817  FORMAT(5X,46H ARMATURE (KG) ................................,F10.4)
 819  FORMAT(5X,46H BINDING MATERIAL (KG) ........................,F10.4)
 821  FORMAT(5X,46H STATOR CORE (KG) .............................,F10.4)
 831  FORMAT(26H ** FEROMAGNETIC SHIELD **)
 833  FORMAT(5X,46H FLUX AT SHIELD RADIUS (TESLA) ................,F10.4)
 835  FORMAT(5X,46H SHIELD OUTER RADIUS (M) ......................,F10.4)
```

```
837   FORMAT(5X,46H SHIELD INNER RADIUS (M) .....................,F10.4)
839   FORMAT(5X,46H MAX. SHIELD FLUX DENSITY (TESLA) ............,F10.4)
841   FORMAT(13H ** LOSSES **)
843   FORMAT(5X,46H ARMATURE LOSSES (WATTS) .....................,E10.4)
845   FORMAT(5X,46H STATOR CORE LOSSES (WATTS) ..................,F10.4)
847   FORMAT(5X,46H NEGATIVE SEQUENCE LOSSES (WATTS) ............,E10.4)
849   FORMAT(5X,46H TOTAL LOSSES (WATTS) ****....................,E10.4)
851   FORMAT(5X,46H COST OF LOSSES (KG/WATT LOST) ...............,F10.4)
853   FORMAT(5X,46H TOTAL COST OF LOSSES (KG) ...................,E10.4)
871   FORMAT(16H ** DENSITIES **)
873   FORMAT(5X,46H COPPER (KG/M**3) ............................,F10.4)
875   FORMAT(5X,46H IRON (KG/M**3) ..............................,F10.4)
877   FORMAT(5X,46H ALUMINUM (KG/M**3) ..........................,F10.4)
879   FORMAT(5X,46H STAINLESS STEEL (KG/M**3) ...................,F10.4)
880   FORMAT(5X,46H BINDING MATERIAL (KG/M**3) ..................,F10.4)
881   FORMAT(24H ** PENALTY FUNCTIONS **)
883   FORMAT(5X,46H SHAFT STRESS ................................,F10.4)
885   FORMAT(5X,46H SHAFT CRITICAL SPEED ........................,F10.4)
887   FORMAT(5X,46H SHIELD FLUX LIMIT............................,F10.4)
889   FORMAT(5X,46H FIELD CURRENT LIMIT .........................,F10.4)
891   FORMAT(5X,46H DAMPER STRESS  ..............................,F10.4)
890   FORMAT(5X,46H ARMATURE INSULATION THICKNESS ...............,F10.4)
892   FORMAT(5X,46H ARMATURE DIAMETER ...........................,F10.4)
901   FORMAT(11H ** COST **)
905   FORMAT(5X,46H COST FUNCTION ...............................,E10.4)
907   FORMAT(5X,46H PENALIZED COST FUNCTION .....................,E10.4)
911   FORMAT(25H ** MATERIAL CONSTANTS **)
913   FORMAT(5X,46H MAX SHEAR STRESS IN DAMPER MATERIAL  ........,E10.4)
915   FORMAT(5X,46H MAX SHEAR STRESS IN TORQUE TUBE MATERIAL ....,E10.4)
917   FORMAT(5X,46H YOUNG'S MODULUS .............................,E10.4)
919   FORMAT(5X,46H POISSON'S RATIO  ............................,F10.4)
5000  FORMAT('1')
100   RETURN
      END
```

```
      FUNCTION CM(P,X,W)
C**** CALC GEOMETRIC COEF. CM ****
      IF(P-2.0)1000,1100,1000
 1100 CM=0.125*(-ALOG10(X )+0.03125*(1.0-X*X)*W**4)
      GO TC 1111
 1000 AA=2.C-P
      BB=2.0+P
      CC=2.0*P
      CM=((1.0-X**AA)+(AA/BB)*(1.0-X**BB)*(W**CC))/
     1/(P*(4.0-P**2))
 1111 RETURN
      END
      FUNCTION CS(P,X,W)
C**** CALC GEOMETRIC COEF. CS ****
      IF (-2.0) 1000,1100,1000
 1100 CS=((X**4*(ALOG10(X)))/20.0)+((1.0-X**4/8.0)
     1+((((1.0-X**4)**2)/16.0)*W**4)
      GO TO 1111
 1000 AA=2.0-P
      BB=2.0+P
      CC=2.0*P
      CS=((AA-(4.0*X**BB)+(BB*X**4)+(2.0*AA/BB*
     1((1.0-X**BB)**2))*(W**CC))/(P*(4.0-P**2)))
 1111 RETURN
      END
```

APPENDIX B

Output of 20,000 Horsepower Generator Optimization

```
        SUPERCONDUCTING GENERATOR/MOTOR DESIGN


----------------------------------------------------------------------

** RATING **
     RATED POWER (HP)..............................    20107.
     RATED POWER (MVA).............................       15.
     POWER FACTOR .................................    1.000
     MECHANICAL SPEED (RPM)........................    3600.
     NUMBER OF POLE PAIRS .........................       1.
     TERMINAL VOLTAGE (V)..........................       1.
     ARMATURE CURRENT (A)..........................0.3500E 07
     PER UNIT POWER RATING (P.U.)..................     1.00


----------------------------------------------------------------------

** ARMATURE **
     ARMATURE THICKNESS (M)........................   0.0957
     ARMATURE TO CORE GAP (M)......................   0.0272
     ARMATURE OUTER RADIUS (M).....................   0.3098
     AVER ALL ARMATURE LENGTH (M)..................   1.0978
     ACTIVE ARMATURE LENGTH (M)....................   0.6846
     STRAIGHT SECTION LENGTH (M)...................   0.5740
     VOLT PER TURN (RMS)...........................  45.43466
     ARMATURE AMPERE-TURNS (RMS/PHASE).............0.9188E 05
     ARMATURE WINDING SPACE FACTOR ................   0.3000
     NO. OF ARMATURE PHASES .......................   3.0000
     ARMATURE CONDUCTIVITY (S/M) ..................0.6000E 08
     ARMATURE ANGLE (RAD) .........................   1.0470


----------------------------------------------------------------------

** FIELD WINDING **
     FIELD THICKNESS (M) ..........................   0.0269
     FIELD INNER RADIUS (M)........................   0.0972
     FIELD TO DAMPER GAP (M) ......................   0.0225
     ACTIVE MACHINE LENGTH (M) ....................   0.6846
     OVERALL FIELD LENGTH (M) .....................   0.9059
     FIELD CURRENT DENSITY (A/M**2) ...............0.1575E 09
     FIELD WINDING SPACE FACTOR ...................   0.5000
     FIELD ELECTRICAL WINDING ANGLE (RAD) ........   2.0940
     FIELD AMPERE-TURNS (A-T) .....................0.9819E 06
     MAX PER UNIT FIELD CURRENT (P.U.).............     1.10
     MAXIMUM FIELD (TESLA) ........................       4.
     SYNCHRONOUS REACTANCE ........................   1.3800
     TRANSIENT REACTANCE ..........................   1.1845
     SUBTRANSIENT REACTANCE .......................   1.2017
```

```
----------------------------------------------------------------------

** DAMPER **
     DAMPER THICKNESS (M) .........................    0.0448
     DAMPER OUTER RADIUS (M) ......................    0.1914
     DAMPER TO ARMATURE GAP (M) ...................    0.0227
     OVERALL DAMPER LENGTH (M) ....................    1.0226
     ARMATURE COUPLING LENGTH (M) .................    0.9119
     DAMPER CONDUCTIVITY ........................0.2000E 08


----------------------------------------------------------------------

** STABILITY **
     TRANSFORMER REACTANCE ........................    0.1000
     REACTANCE UNFAULTED LINE .....................    0.1000
     READTANCE FAULTED LINE .......................    0.1000


----------------------------------------------------------------------

** NATURAL FREQUENCY **
     ROTOR CRITICAL SPEED (RPM) ...................     586.3
     BEARING SPAN (M) .............................    1.5226


----------------------------------------------------------------------

** WEIGHT **
     STAINLESS STEEL SUPPORT (KG) .................   68.6900
     SHIELD WINDING (KG) ..........................  126.4667
     ARMATURE (KG) ................................  456.5620
     BINDING MATERIAL (KG) ........................    0.0017
     STATOR CORE (KG) ............................. 2523.6330


----------------------------------------------------------------------

** FEROMAGNETIC SHIELD **
     FLUX AT SHIELD RADIUS (TESLA) ................    0.6361
     SHIELD OUTER RADIUS (M) ......................    0.4595
     SHIELD INNER RADIUS (M) ......................    0.3370
     MAX. SHIELD FLUX DENSITY (TESLA) .............    1.7500


----------------------------------------------------------------------

** LOSSES **
     ARMATURE LOSSES (WATTS) ....................0.1177E 06
     STATOR CORE LOSSES (WATTS) ...................  599.4370
```

```
     NEGATIVE SEQUENCE LOSSES (WATTS) ...........0.3569E 03
     TOTAL LOSSES (WATTS) ****...................0.1186E 06
     COST OF LOSSES (KG/WATT LOST) ..............    0.0268
     TOTAL COST OF LOSSES (KG) ..................0.3175E 04


----------------------------------------------------------------------

** DENSITIES **
     COPPER (KG/M**3) ........................... 9800.0000
     IRON (KG/M**3) ............................. 7500.0000
     ALUMINUM (KG/M**3) ......................... 2600.0000
     STAINLESS STEEL (KG/M**3) .................. 8000.0000
     BINDING MATERIAL (KG/M**3) ................. 1800.0000


----------------------------------------------------------------------

** PENALTY FUNCTIONS **
     SHAFT STRESS ...............................    1.0000
     SHAFT CRITICAL SPEED .......................    0.9344
     SHIELD FLUX LIMIT...........................    0.9000
     FIELD CURRENT LIMIT ........................    0.9051
     DAMPER STRESS  .............................    0.9000
     ARMATURE INSULATION THICKNESS ..............    0.9152
     ARMATURE DIAMETER ..........................    0.9010


----------------------------------------------------------------------

** COST **
     COST FUNCTION ..............................0.3175E 04
     PENALIZED COST FUNCTION ....................0.1794E 04


----------------------------------------------------------------------

** MATERIAL CONSTANTS **
     MAX SHEAR STRESS IN DAMPER MATERIAL  ........0.2400E 09
     MAX SHEAR STRESS IN TORQUE TUBE MATERIAL ....0.4500E 09
     YOUNG'S MODULUS ............................0.2000E 12
     POISSON'S RATIO  ...........................    0.3000


----------------------------------------------------------------------
```

APPENDIX C

Output of 40,000 Horsepower Motor Optimization

```
          SUPERCONDUCTING GENERATOR/MOTOR DESIGN

----------------------------------------------------------------------

** RATING **
     RATED POWER (HP)..............................    40214.
     RATED POWER (MVA).............................       30.
     POWER FACTOR .................................    1.000
     MECHANICAL SPEED (RPM)........................     200.
     NUMBER OF POLE PAIRS .........................        3.
     TERMINAL VOLTAGE (V)..........................        1.
     ARMATURE CURRENT (A)..........................0.3500E 07
     PER UNIT POWER RATING (P.U.)..................     1.00


----------------------------------------------------------------------

** ARMATURE **
     ARMATURE THICKNESS (M)........................   0.1739
     ARMATURE TO CORE GAP (M)......................   0.0309
     ARMATURE OUTER RADIUS (M).....................   0.7292
     AVER ALL ARMATURE LENGTH (M)..................   1.7877
     ACTIVE ARMATURE LENGTH (M)....................   1.5085
     STRAIGHT SECTION LENGTH (M)...................   1.3596
     VOLT PER TURN (RMS)........................... 19.49800
     ARMATURE AMPERE-TURNS (RMS/PHASE).............0.4092E 06
     ARMATURE WINDING SPACE FACTOR ................   0.3000
     NO. OF ARMATURE PHASES .......................   3.0000
     ARMATURE CONDUCTIVITY (S/M) ..................0.6000E 08
     ARMATURE ANGLE (RAD) .........................   1.0470


----------------------------------------------------------------------

** FIELD WINDING **
     FIELD THICKNESS (M) ..........................   0.0310
     FIELD INNER RADIUS (M)........................   0.4315
     FIELD TO DAMPER GAP (M) ......................   0.0225
     ACTIVE MACHINE LENGTH (M) ....................   1.5085
     OVERALL FIELD LENGTH (M) .....................   1.8065
     FIELD CURRENT DENSITY (A/M**2) ...............0.1432E 09
     FIELD WINDING SPACE FACTOR ...................   0.5000
     FIELD ELECTRICAL WINDING ANGLE (RAD) .........   2.0940
     FIELD AMPERE-TURNS (A-T) .....................0.4152E 07
     MAX PER UNIT FIELD CURRENT (P.U.).............     1.14
     MAXIMUM FIELD (TESLA) ........................       4.
     SYNCHRONOUS REACTANCE ........................   1.0049
     TRANSIENT REACTANCE ..........................   0.8668
     SUBTRANSIENT REACTANCE .......................   0.8643
```

```
--------------------------------------------------------------------

** DAMPER **
     DAMPER THICKNESS (M) ........................    0.0449
     DAMPER OUTER RADIUS (M) .....................    0.5298
     DAMPER TO ARMATURE GAP (M) ..................    0.0255
     OVERALL DAMPER LENGTH (M) ...................    1.8468
     ARMATURE COUPLING LENGTH (M) ................    1.6978
     DAMPER CONDUCTIVITY .........................0.2000E 08


--------------------------------------------------------------------

** STABILITY **
     TRANSFORMER REACTANCE .......................    0.1000
     REACTANCE UNFAULTED LINE ....................    0.1000
     READTANCE FAULTED LINE ......................    0.1000


--------------------------------------------------------------------

** NATURAL FREQUENCY **
     ROTOR CRITICAL SPEED (RPM) ..................    1905.9
     BEARING SPAN (M) ............................    2.3468


--------------------------------------------------------------------

** WEIGHT **
     STAINLESS STEEL SUPPORT (KG) ................ 2036.2830
     SHIELD WINDING (KG) .........................  687.1162
     ARMATURE (KG) ............................... 3311.5050
     BINDING MATERIAL (KG) .......................    0.0132
     STATOR CORE (KG) ............................ 7309.2100


--------------------------------------------------------------------

** FERROMAGNETIC SHIELD **
     FLUX AT SHIELD RADIUS (TESLA) ...............    0.7367
     SHIELD OUTER RADIUS (M) .....................    0.8667
     SHIELD INNER RADIUS (M) .....................    0.7601
     MAX. SHIELD FLUX DENSITY (TESLA) ............    1.7500


--------------------------------------------------------------------

** LOSSES **
     ARMATURE LOSSES (WATTS) .....................0.8535E 06
     STATOR CORE LOSSES (WATTS) .................. 2428.8020
```

```
     NEGATIVE SEQUENCE LOSSES (WATTS) .............0.1177E 04
     TOTAL LOSSES (WATTS) ****.....................0.8571E 06
     COST OF LOSSES (KG/WATT LOST) ...............    0.0156
     TOTAL COST OF LOSSES (KG) ....................0.1339E 05


----------------------------------------------------------------------

** DENSITIES **
     COPPER (KG/M**3) ............................ 8800.0000
     IRON (KG/M**3) .............................. 7500.0000
     ALUMINUM (KG/M**3) .......................... 2600.0000
     STAINLESS STEEL (KG/M**3) ................... 8000.0000
     BINDING MATERIAL (KG/M**3) .................. 1800.0000


----------------------------------------------------------------------

** PENALTY FUNCTIONS **
     SHAFT STRESS ................................    1.0000
     SHAFT CRITICAL SPEED ........................    0.9010
     SHIELD FLUX LIMIT............................    0.9000
     FIELD CURRENT LIMIT .........................    0.9008
     DAMPER STRESS ...............................    0.9000
     ARMATURE INSULATION THICKNESS ...............    0.9026
     ARMATURE DIAMETER ...........................    0.9001


----------------------------------------------------------------------

** COST **
     COST FUNCTION ................................0.1339E 05
     PENALIZED COST FUNCTION ......................0.7154E 04


----------------------------------------------------------------------

** MATERIAL CONSTANTS **
     MAX SHEAR STRESS IN DAMPER MATERIAL  .........0.2400E 09
     MAX SHEAR STRESS IN TORQUE TUBE MATERIAL .....0.4500E 09
     YOUNG'S MODULUS ..............................0.2000E 12
     POISSON'S RATIO  ............................    0.3000


----------------------------------------------------------------------
```

APPENDIX D

Output of 30,000 Horsepower Motor Optimization

```
          SUPERCONDUCTING GENERATOR/MOTOR DESIGN


------------------------------------------------------------------

** RATING **
     RATED POWER (HP)..............................    30161.
     RATED POWER (MVA).............................       23.
     POWER FACTOR .................................    1.000
     MECHANICAL SPEED (RPM)........................     200.
     NUMBER OF POLE PAIRS .........................       3.
     TERMINAL VOLTAGE (V)..........................       1.
     ARMATURE CURRENT (A)........................0.3500E 07
     PER UNIT POWER RATING (P.U.)..................     1.00


------------------------------------------------------------------

** ARMATURE **
     ARMATURE THICKNESS (M)........................   0.1772
     ARMATURE TO CORE GAP (M)......................   0.0313
     ARMATURE OUTER RADIUS (M).....................   0.6998
     AVER ALL ARMATURE LENGTH (M)..................   1.4645
     ACTIVE ARMATURE LENGTH (M)....................   1.1942
     STRAIGHT SECTION LENGTH (M)...................   1.0570
     VOLT PER TURN (RMS)...........................  15.44257
     ARMATURE AMPERE-TURNS (RMS/PHASE)...........0.3568E 06
     ARMATURE WINDING SPACE FACTOR ................   0.3000
     NO. OF ARMATURE PHASES .......................   3.0000
     ARMATURE CONDUCTIVITY (S/M) ................0.6000E 08
     ARMATURE ANGLE (RAD) .........................   1.0470


------------------------------------------------------------------

** FIELD WINDING **
     FIELD THICKNESS (M) ..........................   0.0371
     FIELD INNER RADIUS (M)........................   0.3929
     FIELD TO DAMPER GAP (M) ......................   0.0225
     ACTIVE MACHINE LENGTH (M) ....................   1.1942
     OVERALL FIELD LENGTH (M) .....................   1.4685
     FIELD CURRENT DENSITY (A/M**2) .............0.1436E 09
     FIELD WINDING SPACE FACTOR ...................   0.5000
     FIELD ELECTRICAL WINDING ANGLE (RAD) .........   2.0940
     FIELD AMPERE-TURNS (A-T) ...................0.4585E 07
     MAX PER UNIT FIELD CURRENT (P.U.).............     1.11
     MAXIMUM FIELD (TESLA) ........................       4.
     SYNCHRONOUS REACTANCE ........................   0.9793
     TRANSIENT REACTANCE ..........................   0.8719
     SUBTRANSIENT REACTANCE .......................   0.8607
```

```
---------------------------------------------------------------

** DAMPER **
     DAMPER THICKNESS (M) ........................     0.0449
     DAMPER OUTER RADIUS (M) .....................     0.4974
     DAMPER TO ARMATURE GAP (M) ..................     0.0253
     OVERALL DAMPER LENGTH (M) ...................     1.5108
     ARMATURE COUPLING LENGTH (M) ................     1.3736
     DAMPER CONDUCTIVITY .........................0.2000E 08


---------------------------------------------------------------

** STABILITY **
     TRANSFORMER REACTANCE .......................     0.1000
     REACTANCE UNFAULTED LINE ....................     0.1000
     READTANCE FAULTED LINE ......................     0.1000


---------------------------------------------------------------

** NATURAL FREQUENCY **
     ROTOR CRITICAL SPEED (RPM) ..................     2248.2
     BEARING SPAN (M) ............................     2.0108


---------------------------------------------------------------

** WEIGHT **
     STAINLESS STEEL SUPPORT (KG) ................ 1482.2270
     SHIELD WINDING (KG) .........................  526.3306
     ARMATURE (KG) ............................... 2630.2230
     BINDING MATERIAL (KG) .......................    0.0099
     STATOR CORE (KG) ............................ 5587.0660


---------------------------------------------------------------

** FEROMAGNETIC SHIELD **
     FLUX AT SHIELD RADIUS (TESLA) ...............     0.7428
     SHIELD OUTER RADIUS (M) .....................     0.8345
     SHIELD INNER RADIUS (M) .....................     0.7310
     MAX. SHIELD FLUX DENSITY (TESLA) ............     1.7500


---------------------------------------------------------------

** LOSSES **
     ARMATURE LOSSES (WATTS) .....................0.6779E 06
     STATOR CORE LOSSES (WATTS) .................. 1893.3330
```

```
     NEGATIVE SEQUENCE LOSSES (WATTS) ............0.8892E 03
     TOTAL LOSSES (WATTS) ****....................0.6807E 06
     COST OF LOSSES (KG/WATT LOST) ..............    0.0150
     TOTAL COST OF LOSSES (KG) ..................0.1023E 05


-----------------------------------------------------------------

** DENSITIES **
     COPPER (KG/M**3) ........................... 8800.0000
     IRON (KG/M**3) ............................. 7500.0000
     ALUMINUM (KG/M**3) ......................... 2600.0000
     STAINLESS STEEL (KG/M**3) .................. 8000.0000
     BINDING MATERIAL (KG/M**3) ................. 1800.0000


-----------------------------------------------------------------

** PENALTY FUNCTIONS **
     SHAFT STRESS ...............................    1.0000
     SHAFT CRITICAL SPEED .......................    0.9010
     SHIELD FLUX LIMIT...........................    0.9000
     FIELD CURRENT LIMIT ........................    0.9071
     DAMPER STRESS  .............................    0.9000
     ARMATURE INSULATION THICKNESS ..............    0.9030
     ARMATURE DIAMETER ..........................    0.9001


-----------------------------------------------------------------

** COST **
     COST FUNCTION ..............................0.1023E 05
     PENALIZED COST FUNCTION ....................0.5503E 04


-----------------------------------------------------------------

** MATERIAL CONSTANTS **
     MAX SHEAR STRESS IN DAMPER MATERIAL  ........0.2400E 09
     MAX SHEAR STRESS IN TORQUE TUBE MATERIAL ....0.4500E 09
     YOUNG'S MODULUS .............................0.2000E 12
     POISSON'S RATIO  ............................    0.3000


-----------------------------------------------------------------
```

APPENDIX E

Definition of Input and Search Variables

Input Variables

These variables are arranged in alphabetical order by their names as used in the computer program.

SYMBOL	UNITS	DEFINITION
AJA		Armature current density
BSMAX	T	Maximum flux density in iron shield
DMAX	N/M^2	Maximum shear stress in damper material
DV		A vector of initial stepsizes. Units and variables correspond to the elements of V.
DVL		A vector of Maximum variable increments. The ratio between step-to-step increment of variable cannot exceed the corresponding entry of DVL. Variables correspond to the elements of V.
E	N/M^2	Young's modolus of the torque tube material.
EAL	N/M^2	Young's modolus of the damper material.
EPSI		Optimization fineness criterion
GAMMA		Exponent used in stator core loss calculations
GKI	M	Damper insulation layer thickness.
HC	A/M	A five-element vector of magnetic field intensities used together with JC for defining superconductor H-J curve.
I2	Per-unit	Negative sequence tolerance requirement.

SYMBOL	UNITS	DEFINITION
JC	A/M^2	A five-element vector of current densities used together with HC for defining superconductor H-J curve.
KBFL		Factor assigning part of field end turn length to active machine length.
KBKL		Factor assigning part of armature end turn length to active machine length for coupling to damper.
KBL		End-winding modification factor. Rule-of-thumb armature and damper effective end winding lengths are multiplied by this factor.
KVAPU	Per-unit	Volt-amperes used for critical clearing time calculation.
KWA		Armature winding factor.
LTH		Length of thermal distance piece at one end
NPA		Number of phases-armature
NUMIT		Number of iterative optimization steps. If set to zero CF calculates everything for the input data and optimization is done.
PF		Power Factor
POLE		Number of Poles
PR		Poisson's ratio for torque-tube material.
PZ	w/KG	Dissipation density of core material at max flux density.
ROAL	KG/M^3	Density of damper material

SYMBOL	UNITS	DEFINITION
ROB	KG/M^3	Density of binding material
ROCU	KG/M^3	Density of armature conductors
ROFE	KG/M^3	Density of core iron
ROSS	KG/M^3	Density of torque tube material
RP		Cryogenic refrigerator penalty (Watts input per watt at 4°K)
RPM	REV/MIN	Machine speed
SFA		Armature conductor winding space factor
SFF		Field conductor winding space factor
SIGMAA	S/M	Conductivity of armature conductor
SIGMAK	S/M	Conductivity of damper material
THWAE	RADIANS	Armature phase belt angle (electrical)
THWFE	RADIANS	Field winding angle (electrical)
TMAX	N/M^2	Max shear stress in torque material
TW		Fraction of DV used as trial stepsize in stepsize determining routine.
V		Initial array of dimensions and current density.(see Table I.1)
VA	Volt-amperes	Machine rating
VT	Per-unit	Terminal voltage for critical clearing time calculation.
XT	Per-unit	Transformer reactance

SYMBOL	UNITS	DEFINITION
X1	Per-unit	Reactance of unfaulted line
X2	Per-unit	Reactance of faulted line

Table E.1

SEARCH VARIABLES

VARIABLE	SYMBOL	V SYMBOL	DEFINITION
R_{fi}	RFI	V(1)	Field winding inner radius
t_f	THF	V(2)	Field winding thickness
g_{fk}	GFK	V(3)	Field winding to damper gap
t_k	THK	V(4)	Damper thickness
g_{ka}	GKA	V(5)	Damper to armature winding gap
t_a	THA	V(6)	Armature thickness
g_{as}	GAS	V(7)	Armature winding to stator core gap
J_f	AJF	V(8)	Field current density

APPENDIX F

Variable Inputs
for
20,000 HP Generator
40,000 HP Motor
30,000 HP Motor

20,000 HP Generator

SYMBOL	VALUE	SYMBOL	VALUE
RFI	.12 M	DV(1)	.012
THF	.026	DV(2)	.0026
GFK	.025	DV(3)	.0025
THK	.05	DV(4)	.005
GKA	.02	DV(5)	.002
THA	.1	DV(6)	.01
GAS	.02	DV(7)	.002
AFJ	1.2×10^8	DV(8)	1.2×10^7
VA	15×10^6 VA		
POLE	2		
RPM	3600 RPM		

40,000 HP Motor

RFI	.36	DV(1)	.036
THF	.026	DV(2)	.0026
GFK	.025	DV(3)	.0025
THK	.05	DV(4)	.005
GKA	.02	DV(5)	.002
THA	.1	DV(6)	.01
GAS	.02	DV(7)	.002
AJF	1.2×10^8	DV(8)	1.2×10^7
VA	30×10^6		
POLE	6		
RPM	200		

30,000 HP Motor

SYMBOL	VALUE	SYMBOL	VALUE
RFI	.40	DV(1)	.04
THF	.026	DV(2)	.0026
GFK	.025	DV(3)	.0025
THK	.05	DV(4)	.005
GKA	.02	DV(5)	.002
THA	.1	DV(6)	.01
GAS	.02	DV(7)	.002
AJF	1.2×10^8	DV(8)	1.2×10^7
VA	22.5×10^6		
POLE	6		
RPM	200		

APPENDIX G

Fixed Inputs for Computer Optimization Program

SYMBOL	VALUE	SYMBOL	VALUE
AJA	3.5×10^6	PF	1.0
BSMAX	1.75	PR	0.3
DMAX	2.4×10^8	PZ	2.65
DVL(1-8)	.1		
E	2×10^{11}	ROAL	2600
EAL	6.94×10^{10}	ROB	1800
GAMMA	2.4	ROCU	8800
EPSI	.005		
GKI	.02	ROFE	7500
HC	see Table G.1	ROSS	8000
I2	.05	RP	1000
JC	see Table G.1	SFA	0.3
KBFL	.5	SFF	0.5
KBKL	1.0	SIGMAA	6×10^7
KBL	1.0	SIGMAK	2×10^7
KVAPU	1.0	THWAE	1.047
KWA	1.0	THWFE	2.094
NPA	3.0	TMAX	4.5×10^8
NUMIT	15	TW	0.1
VT	1.0		
XT	0.1		
X1	0.1		
X2	0.1		

TABLE G.1

HC VECTOR OF MAGNETIC FIELD INTENSITIES AND JC VECTOR OF CURRENT DENSITIES for defining the Superconductor H-J Curve

SYMBOL	VALUE	SYMBOL	VALUE
HC(1)	5.5×10^6	JC(1)	0
HC(2)	4.38×10^6	JC(2)	1×10^8
HC(3)	3.18×10^6	JC(3)	2×10^8
HC(4)	2.0×10^6	JC(4)	3×10^8
HC(5)	$.796\times10^6$	JC(5)	4×10^8

APPENDIX H

Ship Synthesis Model*

*Ship Synthesis Model is the model in Reference (16).

The ship synthesis model is a method for estimating the weight, volume, electric load, speed and other overall ship characteristics of Naval Surface Displacement Ships. This program has been verified to give accurate results for ships which range in size from 300 to 700 feet in length and 1700 to 17,000 tons in displacement. The model does not attempt to define or check the arrangements required for the ship; therefore, highly arrangement dependent calculations cannot be performed. These include damage stability, topside arrangement, internal arrangements, longitudinal balance, and strength calculations.

The synthesis model does provide solutions that satisfy the following requirements. First, there must be a balance between weight and displacement. Second, internal space available must be equal to or greater than internal space required. Third, the energy available must at least meet the energy required to provide internal power and to propel the ship. Finally, the distribution of weight and volume must be such as to satisfy design criteria for transverse stability, girder strength and seakeeping.

The model synthesizes a Naval surface ship from the following relationships:

a. Selecting starting estimates for full load displacement and center of gravity based on a set of relationships and rules.

b. Selecting the proper geometric relationships for Navy surface ships to match the hull form to the displacement and center of gravity.

c. Linear fit for the selected hull form to the resistance and powering curves.

d. Calculating the weight of the specified payload items and other ship equipments to determine a more exact value for full load displacement.

e. Calculate the center of gravity based on specified ship configuration and compare to estimated center of gravity.

f. Calculate the volume required and match this with the calculated hull dimensions.

g. Perform electric load calculations.

h. Compare equipment sizing relationships with the existing ship dimensions.

i. Iterate through the above steps until all of the relationships agree to within a specified tolerance or until the maximum number of iterations has been performed without obtaining viable solution, in which case the ship as specified is infeasible.

```
SHIP NUMBER    2

                              SHIP SPECIFICATIONS

VSUS            0.00    DELTA CF        0.00    CPO ACC        21.00
VEND           20.00                    0.00    CREW ACC      252.00
RANGE        6000.00                    0.00    FLAG ACC        0.00
LBP           529.00                    0.00    TRP ACC         0.00
L/B             9.62                    0.00    PASS ACC        0.00
B/H             2.89    SSEL TYP        3.00    DAYS DUR       45.00
CP              0.59    EMEL TYP        2.00                    0.00
CX              0.83    NU LOWSD        0.00                    0.00
                0.00    NU MEDSD        0.00                    0.00
                0.00    NU HI SD        0.00                    0.00
PROP PLT        6.00    NU GT GN        3.00    HULL MAT        1.00
SUS SHP     80000.00    NU ST GN        0.00    SUPSTMAT        2.00
NU BOILS        0.00    KW/DIESL        0.00                    0.00
NU REACT        0.00    KW/GAS T     2000.00    GM/B MIN        0.10
NU ENGS         4.00    KW/STM G        0.00                    0.00
NU SHAFT        2.00    ELC MARG        0.60    DISP TOL       10.00
PROPELLR        2.00                    0.00    MXDIS IT       20.00
SHFT TYP        1.00                    0.00    VCG TOL         1.00
PROP RPM      169.00                    0.00    MXVCG IT       20.00
PROP DIA       17.00    HEAT TYP        1.00    DCWTMARG        0.00
DEPTH MB        0.00    FIN STAB        1.00    FS CORR         0.00
LENTH MB        0.00                    0.00    PRNT TYP        2.00
BEAM MB         0.00                    0.00    PRNTCNST        1.00
PC END          0.00                    0.00                    0.00
PC MAXSP        0.00    OFF ACC        25.00    PASSAGE         2.00

PROP PLT    GASTURB2    SHFT TYP    HOLLOW      HULL MAT    STEEL
SSEL TYP    GASTURB2    PROPELLR    CONT PIT    SUPSTMAT    ALUMINUM
EMEL TYP    GASTURB2    FIN STAB    NO          PASSAGE     PORTSTBD
                        HEAT TYP    STEAM

                              SPECIAL PAYLOAD INPUT

WT GRP     VOL GRP     WT     VCG NU     VCG REF     AREA SUP     AREA HULL

NO SPECIAL PAYLOAD INPUT
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SHIP NUMBER   2

                      PAYLOAD SPECIFICATIONS

  QNTY ITEM     QNTY ITEM     QNTY ITEM     QNTY ITEM     QNTY ITEM
    1.00   3      1.00 208
    1.00  18      1.00 209
    1.00  27      1.00 213
    1.00  40      4.00 215
    1.00  58      1.00 222
    1.00  66      2.00 230
    1.00  74      1.00 232
    1.00  95      1.00 190
    1.00  96      1.00 242
    2.00 100      1.00 241
    1.00 112      1.00 244
 1200.00 121    100.00 252
36000.00 124
    1.00 148
    1.00 150
    2.00 180
    1.00 186
   16.00 194
    8.00 200
    1.00 204


                        SUMMARY OF RESULTS

LBP            529.00   DISP FLD    7890.66   FLD DENS       17.43
BEAM            56.23   DISP LSP    5826.79   LSP DENS       12.87
DRAFT           18.70   VR LOADS    1963.88   WPAY/FLD        0.05
D 0             40.55   WT MARG      100.00   WPER/FLD        0.03
D 10            33.06   WTGRP 1     3137.13   WOPS/FLD        0.44
D 20            33.59   WTGRP 2      789.18   VPAY/VOL        0.16
D AVG           40.47   WTGRP 3      296.89   VPER/VOL        0.25
LEN R DK       321.06   WTGRP 4      250.28   VOPS/VOL        0.59
CP               0.59   WTGRP 5      739.77   WTG2/SHP       22.10
CX               0.83   WTGRP 6      454.34   VMB/SHP         2.45
VCG FLD         22.27   WTGRP 7      159.20   WT3/KWIN      110.84
VCG/DAVG         0.65   VOL TOT 1014326.00   WTG1/VOL        6.93
L/B              9.41   VOL HULL 773027.60   WTG5/VOL        1.63
B/H              3.01   VOL SSTR 241298.50   VHAB/MAN      724.02
EXCES KG         0.00   CRUISEKW    1595.00   WHAB/MAN      864.71
RANGE         6000.00   BATTLEKW    1725.00   MEN/DISP        0.04
SUS SHP      80000.00   24 HR KW    1600.00   KWIN/FLD        0.76
END SHP      11537.13   NU LOWSD       0.00   SHP/DISP       10.14
VSUS            32.87   NU MEDSD       0.00   DP*V/SHP       22.30
VEND            20.00   NU HI SD       0.00   WPY*V/DP        1.64
AVSEASPD        31.58   NU GT GN       3.00
NU ACCOM       298.00   NU ST GN       0.00
KW INST       6000.00   KW/DIESL       0.00
KW SPSER      6000.00   KW/GAS T    2000.00
KW EMERG         0.00   KW/STM G       0.00
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SHIP NUMBER   2

     SHIP CONSTANTS

ELEMENT NUMBER      VALUE

      2250           1.96
      2251           1.74
      2252           1.49
      2253           1.65
      2254           1.40
      2255           1.39
      2256           1.48
      2257           2.12
      2258           1.76
      2259           1.79
      2260           1.67
      2261           3.32
      2262           2.55
      2263           4.92
      2264           1.49
      2265           2.56
      2266           4.20
      2267           2.46
      2268           4.01
      2269           2.46
      2270           1.98
      2271           2.58
      2272           1.49
      2273           1.56
      2274          10.00
      2275           0.00
      2276           0.00
      2277           0.00
      2278           0.00
      2279           0.00
      2280           0.00
      2281           0.00
      2282           0.00
      2283           0.00
      2284           0.00
      2285           0.00
      2286           0.00
      2287           0.00
      2288           0.00
      2289           0.00
      2290           0.00
      2291           0.00
      2292           0.00
      2293           0.00
      2294           0.00
      2295           0.00
      2296           0.00
      2297           0.00
      2298           0.00
      2299           0.00
```

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SHIP NUMBER   2

                   DETAILED RESULTS--FUNCTIONAL GROUPING

GROUP      NAME      WEIGHT      WT FRAC       VOLUME      VOL FRAC         DENSITY
                      TONS                     CU FT                        LBS/CU FT

 100     MIL MISS    392.8       0.0506       159298.       0.1570             5.52

 110     COMM/DET     71.6       0.0092        86461.       0.0653             1.85
 111     RADIOCOM     17.2       0.0022         5772.       0.0057             6.67
 112     RADAR         6.6       0.0008         2553.       0.0025             5.79
 113     SONAR        12.4       0.0016        24964.       0.0246             1.11
 114     ECM           8.5       0.0011        39964.       0.0394             0.48
 115     EVALUATE      6.1       0.0008         8691.       0.0086             1.57
 116     C/D SUPP     20.8       0.0027         4537.       0.0045            10.26

 120     WEAPONS     279.9       0.0360        42570.       0.0420            14.73
 121     GUNS        164.8       0.0212        20952.       0.0207            17.62
 122     MISSILES      0.0       0.0000            0.       0.0000             0.00
 123     ASW          63.4       0.0082        15540.       0.0153             9.13
 124     MINE WAR      0.0       0.0000            0.       0.0000             0.00
 125     SM ARMS       4.7       0.0006         1499.       0.0015             7.02
 126     CM NO EL     39.4       0.0051            0.       0.0000             0.00
 127     WEAP SUP      7.7       0.0010         4579.       0.0045             3.77
 128     SPECWEAP      0.0       0.0000            0.       0.0000             0.00

 130     AVIATION     36.9       0.0048        30247.       0.0298             2.73
 131     CONTROL      12.4       0.0016         3607.       0.0036             7.68
 132     STOW/MNT     17.9       0.0023        22200.       0.0219             1.80
 133     STORES        6.7       0.0009         4440.       0.0044             3.37
 134     LIQUIDS       0.0       0.0000            0.       0.0000             0.00
 135     ORDNANCE      0.0       0.0000            0.       0.0000             0.00

 140     AMPH OPS      0.0       0.0000            0.       0.0000             0.00
 150     CARGO         0.0       0.0000            0.       0.0000             0.00
 160     FLAG          0.0       0.0000            0.       0.0000             0.00
 170     PASSNGER      0.0       0.0000            0.       0.0000             0.00
 180     SPEC MIS      4.4       0.0006            0.       0.0000             0.00


 200     PERSONEL    238.5       0.0307       251990.       0.2484             2.12

 210     LIVING       69.9       0.0090       154050.       0.1519             1.02
 211     OFF BER       0.0       0.0000        30454.       0.0300             0.00
 212     OFF MESS      0.0       0.0000         7507.       0.0074             0.00
 213     OFF BATH      0.0       0.0000         3347.       0.0033             0.00
 214     CPO BER       0.0       0.0000         9646.       0.0095             0.00
 215     CPO MESS      0.0       0.0000         3462.       0.0034             0.00
 216     CPO BATH      0.0       0.0000         2387.       0.0024             0.00
 217     CREW BER      0.0       0.0000        62826.       0.0619             0.00
 218     CREWMESS      0.0       0.0000        21742.       0.0214             0.00
 219     CREWBATH      0.0       0.0000        12679.       0.0125             0.00
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SHIP NUMBER   2

                DETAILED RESULTS--FUNCTIONAL GROUPING CONTINUED

GROUP    NAME      WEIGHT     WT FRAC     VOLUME      VOL FRAC       DENSITY
                    TONS                  CU FT                    LBS/CU FT

220     SUPPORT     45.2     0.0058      61708.      0.0608          1.64
221     ADMIN FN     2.1     0.0003       2933.      0.0029          1.59
222     FOOD P&H    10.8     0.0014      16436.      0.0162          1.47
223     MED &DEN     3.2     0.0004      11082.      0.0109          0.65
224     PER SERV    15.9     0.0020      15742.      0.0155          2.26
225     REC &WEL     3.2     0.0004      11516.      0.0114          0.62
226     SEWAGE      10.0     0.0013       4000.      0.0039          5.60

230     STOWAGE    123.5     0.0159      36232.      0.0357          7.64
231     STORES      45.1     0.0058      12381.      0.0122          8.16
232     PER STOW    24.9     0.0032      11542.      0.0114          4.84
233     POTWATER    53.5     0.0069      12309.      0.0121          9.73


300     SHIP OPS  3410.7     0.4392     603039.      0.5945         12.67

310     CONTROL    120.1     0.0155      60688.      0.0598          4.43
311     SHIP CNT    98.5     0.0127      26000.      0.0256          8.49
312     DAM CONT     0.0     0.0000       4357.      0.0043          0.00
313     OFFICES     21.6     0.0028      30331.      0.0299          1.59

320     MACH SYS  1259.1     0.1621     292877.      0.2887          9.63
321     MACH BOX   722.2     0.0930     195955.      0.1932          8.26
322     UPTAKES    130.5     0.0168      49150.      0.0485          5.95
323     SH,BR,PR   253.1     0.0326       3848.      0.0038        147.38
324     MANEUVER    81.7     0.0105       7000.      0.0069         26.14
325     VENTILAT    71.6     0.0092      36924.      0.0364          4.34

330     DECK AUX   115.1     0.0148       5194.      0.0051         49.64
331     ANCH,M&T    88.1     0.0113       5094.      0.0050         38.74
332     UNREP       27.0     0.0035        100.      0.0001        604.80

340     MAINTAIN    92.2     0.0119      21370.      0.0211          9.67
341     MECHANIC    18.6     0.0024      12173.      0.0120          3.42
342     ELECTRIC     7.3     0.0009       4815.      0.0047          3.42
343     MISC        66.3     0.0085       4381.      0.0043         33.89

350     STOWAGE   1810.7     0.2332      72599.      0.0716         55.87
351     FUEL OIL  1700.4     0.2190      60393.      0.0595         63.07
352     R FEED W     0.0     0.0000          0.      0.0000          0.00
353     LUBE OIL    15.5     0.0020        604.      0.0006         57.44
354     DIES OIL     0.0     0.0000          0.      0.0000          0.00
355     MISC LIQ     0.0     0.0000          0.      0.0000          0.00
356     STOR&SUP    69.7     0.0090      11601.      0.0114         13.46
357     BOATS       25.1     0.0032          0.      0.0000          0.00
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SHIP NUMBER    2

                 DETAILED RESULTS--FUNCTIONAL GROUPING CONTINUED

GROUP     NAME      WEIGHT      WT FRAC      VOLUME      VOL FRAC        DENSITY
                     TONS                    CU FT                      LBS/CU FT

360     TANKAGE       0.0      0.0000       28278.      0.0279            0.00
361     BALLAST       0.0      0.0000           0.      0.0000            0.00
362     PEAK          0.0      0.0000        3409.      0.0034            0.00
363     VOIDS         0.0      0.0000       24869.      0.0245            0.00
364     XFLOODNG      0.0      0.0000           0.      0.0000            0.00
365     MISC TNK      0.0      0.0000           0.      0.0000            0.00

370     PASS&ACC     13.5      0.0017      122033.      0.1203            0.25
380     HULL MAR      0.0      0.0000           0.      0.0000            0.00
390     SUP MARG      0.0      0.0000           0.      0.0000            0.00

400     HULL GRP   3121.2      0.4019

410     BASCHULL   1326.1      0.1708
420     SEC HULL   1583.0      0.2039
430     DECKHOUS    212.1      0.0273
440     ARMOR         0.0      0.0000
450     FREEFLLQ      0.0      0.0000

500     SHIP SYS    602.4      0.0776

        TOTAL      7765.7      1.0000     1014327.      1.0000           17.15
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SHIP NUMBER   2

        DETAILED RESULTS--BSCI WEIGHT LISTING

GROUP      NAME      WEIGHT      WT FRAC      WT FRAC       VCG
                      TONS       FULL LD      LITE SH        FT

100       PLATING     621.2      0.0787       0.1066       17.2
101       FRAMING     405.8      0.0514       0.0696       13.5
102       INN BOTM    116.1      0.0147       0.0199        5.8
103       PLATFLAT    206.3      0.0261       0.0354       16.7
104                     0.0      0.0000       0.0000        0.0
105                     0.0      0.0000       0.0000        0.0
106                     0.0      0.0000       0.0000        0.0
107       ALL DECK    525.5      0.0666       0.0902       39.2
108                     0.0      0.0000       0.0000        0.0
109                     0.0      0.0000       0.0000        0.0
110                     0.0      0.0000       0.0000        0.0
111       SUPERSTR    212.1      0.0269       0.0364       57.6
112       PROP FNO    187.7      0.0238       0.0322       10.8
113       AUX FNOS    178.8      0.0227       0.0307       14.8
114       STR BKHD    301.9      0.0383       0.0518       24.2
115       TRK&ENCL     65.4      0.0083       0.0112       25.2
116       STR SPON      0.0      0.0000       0.0000        0.0
117       ARMOR         0.0      0.0000       0.0000        0.0
118       AC T STR      0.0      0.0000       0.0000       19.5
119       CAST&FOR     85.5      0.0108       0.0147       16.0
120       SEACHEST      7.2      0.0009       0.0012        5.8
121       BAL UNIT      0.0      0.0000       0.0000        0.0
122       SPEC DRS      8.5      0.0011       0.0015       31.4
123       DRS&HTCH     43.2      0.0055       0.0074       37.8
124                     0.0      0.0000       0.0000        0.0
125       MASTKGPT      6.9      0.0009       0.0012       89.3
127       SONAR DM     63.0      0.0080       0.0108       -4.7
128       TCWRPLAT      0.0      0.0000       0.0000        0.0
150       WELDRIVT     51.9      0.0066       0.0089       25.8
151       FREEFLIQ      0.0      0.0000       0.0000        6.5
          GRP1 TOT   3137.1      0.3976       0.5384       22.9

200       BOIL&CON      0.0      0.0000       0.0000       15.3
201       PROPUNIT    244.1      0.0309       0.0419       16.2
202       MN CONDS      0.0      0.0000       0.0000       10.9
203       SH,BR,PR    253.1      0.0321       0.0434        6.8
204       COMB AIR     58.3      0.0074       0.0100       48.7
205       UPTAKES     130.5      0.0165       0.0224       72.2
206       PROP CNT     11.0      0.0014       0.0019       25.1
207       MN STM S      0.0      0.0000       0.0000       27.2
208       FW&CONDN      0.0      0.0000       0.0000       16.6
209       CIRC&CWS      0.0      0.0000       0.0000       10.8
210       FOSERSYS     10.1      0.0013       0.0017       12.0
211       LBOILSYS     31.2      0.0040       0.0054       14.0
250       REPAIRPT      8.5      0.0011       0.0015       17.8
251       OPER FLD     42.2      0.0054       0.0072       13.9
          GRP2 TOT    789.2      0.1000       0.1354       24.7
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SHIP NUMBER   2

        DETAILED RESULTS--BSCI WEIGHT LISTING CONTINUED

GROUP    NAME      WEIGHT    WT FRAC     WT FRAC      VCG
                    TONS     FULL LD     LITE SH       FT

300     EL PWGEN    111.1    0.0141      0.0191       18.3
301     POW SWBD     20.6    0.0026      0.0035       25.0
302     CABLE       123.6    0.0157      0.0212       29.6
303     LIGHTING     36.5    0.0046      0.0063       37.9
350     REPAIRPT      4.5    0.0006      0.0008       21.9
351     GEN FLDS      0.5    0.0001      0.0001       16.7
        GRP3 TOT    296.9    0.0376      0.0510       25.9

400     NAV EQUP     18.2    0.0023      0.0031       61.9
401     IC SYSTS     76.9    0.0097      0.0132       34.3
402     GFC SYST     11.6    0.0015      0.0020       63.1
403     CM NO EL     39.4    0.0050      0.0068       28.9
404     ECM           8.5    0.0011      0.0015       58.6
405     MFC SYS       0.0    0.0000      0.0000        0.0
406     ASW FCS      29.2    0.0037      0.0050       35.0
407     TORP FCS      0.0    0.0000      0.0000        0.0
408     RADAR         6.6    0.0008      0.0011       65.1
409     RADIOCOM     17.2    0.0022      0.0030       49.6
410     ELEC NAV      3.4    0.0004      0.0006       55.0
411     SPACTRCK      0.0    0.0000      0.0000        0.0
412     SONAR        12.4    0.0016      0.0021        8.5
413     ELEC TDS      6.1    0.0008      0.0010       58.6
415     ELECTEST     12.3    0.0016      0.0021        0.0
450     REPAIRPT      8.5    0.0011      0.0015       31.3
451     CC OPFLD      0.0    0.0000      0.0000        0.0
        GRP4 TOT    250.3    0.0317      0.0430       37.3

500     HEAT SYS     13.6    0.0017      0.0023       34.1
501     VENT SYS     89.5    0.0113      0.0154       40.4
502     AIR COND     46.5    0.0059      0.0080       23.1
503     REFER PL     11.7    0.0015      0.0020       23.1
504     GEAR,ETC     15.7    0.0020      0.0027       28.6
505     PLUMBING     22.6    0.0029      0.0039       33.6
506     PIPEMAIN     62.5    0.0079      0.0107       32.3
507     FIRE EXT     15.6    0.0020      0.0027       34.6
508     BALSTSYS     25.1    0.0032      0.0043       11.6
509     FRESHWAT     29.5    0.0037      0.0051       26.8
510     SCUPPERS      3.6    0.0005      0.0006       34.6
511     FUELTRAN     60.5    0.0077      0.0104       16.4
512     TANKHEAT      0.0    0.0000      0.0000        6.8
513     COMP AIR     42.1    0.0053      0.0072       16.4
514     AUX STM      13.5    0.0017      0.0023       14.5
515     BUOY CNT      0.0    0.0000      0.0000        0.0
516     MISCPIPE      0.0    0.0000      0.0000       13.3
517     DISTILLG      9.0    0.0011      0.0015       20.3
518     STEERING     24.7    0.0031      0.0042       20.8
519     RUDDERS      57.0    0.0072      0.0098       14.4
520     ANCH,E&T     70.5    0.0089      0.0121       30.7
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SHIP NUMBER   2

        DETAILED RESULTS--BSCI WEIGHT LISTING CONTINUED

GROUP     NAME       WEIGHT      WT FRAC      WT FRAC      VCG
                      TONS       FULL LD      LITE SH       FT

521      STOR EQP     10.8       0.0014       0.0019       45.5
522      ELOPGEAR      0.0       0.0000       0.0000        0.0
523      AIR ELEV      0.0       0.0000       0.0000        0.0
524      ACARGEAR      0.0       0.0000       0.0000        0.0
525      CATS&JBD      0.0       0.0000       0.0000        0.0
526      HYDROFLS      0.0       0.0000       0.0000        0.0
527      STAB FIN      0.0       0.0000       0.0000        9.1
528      UNREP        27.0       0.0034       0.0046       43.1
550      REPAIRPT      3.5       0.0004       0.0006       20.6
551      AUX FLDS     37.4       0.0047       0.0064       24.3
         GRP5 TOT    739.8       0.0938       0.1270       25.1

600      HULL FIT     17.6       0.0022       0.0030       45.3
601      BOATS        25.1       0.0032       0.0043       53.1
602      RIG&CANV      0.9       0.0001       0.0002       54.8
603      LAD&GRAT     40.5       0.0051       0.0070       20.5
604      NONS B&D     30.6       0.0039       0.0053       40.5
605      PAINTING     58.7       0.0074       0.0101       26.1
606      DK COVER     29.8       0.0038       0.0051       37.9
607      HULL INS     58.9       0.0075       0.0101       34.1
608      STORERMS     58.6       0.0074       0.0101       26.9
609      UTIL EQP     15.9       0.0020       0.0027       31.4
610      WKSP EQP     32.6       0.0041       0.0056       36.1
611      GALY EQP     10.8       0.0014       0.0019       39.0
612      LIV FURN     40.5       0.0051       0.0070       36.4
613      OFF FURN     26.2       0.0033       0.0045       44.9
614      MED FURN      3.2       0.0004       0.0005       33.2
615      RAD SHLD      0.0       0.0000       0.0000        0.0
650      REPAIRPT      2.2       0.0003       0.0004       34.2
651      O&F FLDS      0.0       0.0000       0.0000        0.0
         GRP6 TOT    454.3       0.0576       0.0780       33.9

700      GUN MNTS     83.1       0.0105       0.0143       50.4
701                    0.0       0.0000       0.0000        0.0
702                    0.0       0.0000       0.0000        0.0
703      SPWEPH&S      0.0       0.0000       0.0000        0.0
704      MIS LH&S     46.7       0.0059       0.0080       44.9
705                    0.0       0.0000       0.0000        0.0
706                    0.0       0.0000       0.0000        0.0
707                    0.0       0.0000       0.0000        0.0
708      TORPTH&S      8.6       0.0011       0.0015       46.1
709                    0.0       0.0000       0.0000        0.0
710      MINE H&S      0.0       0.0000       0.0000        0.0
711      SM ARMS       4.7       0.0006       0.0008       43.1
712      AIR H&ST      0.0       0.0000       0.0000        0.0
713                    0.0       0.0000       0.0000        0.0
720      CARGOH&S      0.0       0.0000       0.0000        0.0
750      REPAIRPT      6.1       0.0008       0.0010       25.0
751      ARM FLDS      1.6       0.0002       0.0003       32.7
         GRP7 TOT    159.2       0.0202       0.0273       44.5
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SHIP NUMBER   2

       DETAILED RESULTS--BSCI WEIGHT LISTING CONTINUED

GROUP      NAME      WEIGHT      WT FRAC      VCG
                      TONS       FULL LD       FT

800     SHIP OCE     33.4      0.0042       31.9
801     TRPS&EFF      0.0      0.0000       31.9
802     PASS&EFF      0.0      0.0000       31.9
803     SHIPAMMO     79.5      0.0101       34.6
804     AV AMMO       0.0      0.0000        0.0
805     AIRCRAFT     17.9      0.0023       50.1
806     PROV&PST     45.1      0.0057       22.6
807     GEN STOR     11.9      0.0015       25.8
808     MARINEST      0.0      0.0000        0.0
809     AERO STR      6.7      0.0008       34.4
810     ORDSTRSH      0.0      0.0000        0.0
811     ORDSTRAV      0.0      0.0000        0.0
812     POTWATER     53.5      0.0068        4.2
813     R FEED W      0.0      0.0000        4.7
814     LUBOILSH     15.5      0.0020       19.3
815     LUBOILAV      0.0      0.0000        0.0
816     FUEL OIL   1700.4      0.2155        9.0
817     DIES OIL      0.0      0.0000       12.5
818     GASOLINE      0.0      0.0000        0.0
819     JP-5          0.0      0.0000        0.0
820     MISC LIQ      0.0      0.0000        0.0
821     CARGO         0.0      0.0000        0.0
822     BALL WAT      0.0      0.0000        0.0

      VRLOAD TOT   1963.9      0.2489       11.2
      LIGHT SHIP   5826.8      0.7384       25.6
       WT MARGIN    100.0      0.0127       43.1

  FULL LOAD DISP   7890.7      1.0000       22.3


                 DETAILED RESULTS--FUNCTIONAL ELECTRIC LOADS

GROUP      NAME     CRUISE KW     BATTLE KW     24 HR AVG KW

100     PA&STEER     384.5         443.4           306.2
200     AUX MACH     342.2         422.7           476.4
300     DECKMACH       2.0           1.5             0.3
400     SHOPS          6.9           1.2             5.4
500     IC&ELEX      223.8         264.9           226.3
600     ORDN SYS      25.6         202.1            12.1
700     HOTEL        192.9         127.4           159.5
800     A/C&VENT     958.3         495.2           692.4
900     PWR CONV     110.0         214.6            99.4
        ELECMARG    1399.1        1395.3          1186.8

        TOTAL KW    1595.0        1725.0          1600.0
```

SAMPLE INPUT

```
C     SHIP CHARACTERISTIC INPUTS

1 0 20 6000 529 9.62 2.89 .59 .831 0 0 6 80000
13 0 0 4 2 2 1 169 17
31 3 2 0 0 0 3 0 2000 0 .6 0 0 0 1 1

C     CREW & STORES ENDURANCE

50 25 21 252 0 0 0 45

C    SHIP GEOMETRY TOLLERANCES

61 1 2 0 .1 0 10 20 1 20
72 2 1 0 2

C     SHIP PAYLOAD

100 1 3 1 18 1 27 1 40 1 58 1 66 1 74
114 1 95 1 96 2 100 1 112 1200 121 36000 124 1 148
121 1 150 2 180
132 1 186 16 194 8 200 1 204 1 208 1 209 1 213
140 4 215 1 222 2 230
152 1 232 1 190 1 242 1 241 1 244 100 252

C     INPUT OF WTGP 2

401 244.14 0 253.15 58.34 130.51 10.97 0 0 0 10.1 31.24
450 8.5 42.23

C     INPUT OF WTGP 3

500 111.14
550 4.5 0.54

C     ELECTRIC LOAD SPECIFICATIONS

2201 342.2
2210 1595
2212 422.7
2221 1725
2232 1600
```

```
C     MULTIPLIERS OF VOLUME GROUPS

2250 1.96 1.74 1.49 1.65 1.40 1.39 1.48 2.12 1.76 1.79
2261 1.67 3.32 2.55
2263 4.92 1.49 2.56 4.20 2.46 4.01 2.46 1.98 2.58
2272 1.49 1.56 10.0
```

APPENDIX I

BSCI Weight Groups - detailed listing

MODIFIED BSCI WEIGHT GROUPS

Sub Group	Description
Hull Structure--Group 1	
100	Shell Plating
101	Longitudinal & Transverse Framing
102	Inner Bottom Plating
103	Platforms & Flats
107	All Decks (BSCI 104 thru 110)
111	Superstructure
112	Propulsion Foundations
113	Foundations for Aux. & Other Equip.
114	Structural Bulkheads
115	Trunks & Enclosures
116	Structural Sponsons
117	Armor
118	Aircraft Saddle Tank Structure
119	Castings & Forgings
120	Sea Chests
121	Ballast & Buoyancy Units
122	Special Doors & Closures
123	Doors & Hatches (BSCI 123 & 124)
125	Masts & Kingposts
127	Sonar Domes
128	Towers & Platforms
150	Welding, Riveting & Fastenings
151	Free Flooding Liquids
Propulsion--Group 2	
200	Boilers and Energy Converters (Includes Nuclear)
201	Propulsion Units
202	Main Condensers & Air Ejectors
203	Shafting, Bearings & Propellers
204	Combustion Air Supply
205	Uptakes & Smoke Pipes
206	Propulsion Control Equipment
207	Main Steam System
208	Feed Water & Condensate System
209	Circulating & Cooling Water System
210	Fuel Oil Service Systems
211	Lubricating Oil System
250	Propulsion Repair Parts
251	Propulsion Operating Fluids
Electric Plant--Group 3	
300	Electric Power Generation

Sub Group	Description
301	Power Distribution Switchboards
302	Power Distribution System (Cable)
303	Lighting System
350	Electric Plant Repair Parts
351	Electric Power Generator Fluids
Communication and Control--Group 4	
400	Navigation Equipment
401	Interior Communication Systems
402	Gun Fire Control Systems
403	Countermeasure System (Non-Electronic)
404	Electronic Countermeasure Systems (ECM)
405	Missile Fire Control Systems
406	ASW Fire Control & Torpedo Fire Control System
407	Torpedo Fire Control System--Submarines
408	Radar Systems
409	Radio Communication Systems
410	Electronic Navigation Systems
411	Space Vehicle Electronic Tracking Systems
412	Sonar Systems
413	Electronic Tactical Data Systems
415	Electronic Test, Checkout & Monitoring Equipment
450	Communication and Control Repair Parts
451	Communication and Control Operating Fluids
Auxiliary Systems--Group 5	
500	Heating System
501	Ventilation System
502	Air Conditioning System
503	Refrigerating Spaces, Plant & Equipment
504	Gas, HEAF, All Liquid Cargo Piping, Aviation Lube Oil System, Sewage System
505	Plumbing Installations
506	Firemain, Flushing, Sprinkler, S.W. Service Systems
507	Fire Extinguishing System
508	Drainage, Ballast, Stabilizing Tank System

Sub Group	Description
509	Fresh Water System
510	Scuppers and Deck Drains
511	Fuel & Diesel Oil Filling, Venting, Stowage & Transfer System
512	Tank Heating Systems
513	Compressed Air Systems
514	Auxiliary Steam, Exhaust Steam & Steam Drains
515	Buoyancy Control System, Submarines
516	Miscellaneous Piping Systems
517	Distilling Plant
518	Steering Systems
519	Rudders
520	Mooring, Towing, Anchor & Aircraft, Handling System & Deck Machinery
521	Elevators, Moving Stairways, Stores Handling Systems
522	Operating Gear for Retracting & Elevating Units
523	Aircrafts Elevators
524	Aircraft Arresting Gear, Barriers & Barricades
525	Catapults and Jet Blast Deflectors
526	Hydrofoils
527	Diving Planes & Stabilizing Fins
528	Replenishment at Sea & Cargo Handling
550	Auxiliary Systems Repair Parts
551	Auxiliary Systems Operating Fluids

Outfit and Furnishings--Group 6

600	Hull Fittings
601	Boats, Boat Stowage & Handling
602	Rigging & Canvas
603	Ladders & Gratings
604	Nonstructural Bulkheads & Doors
605	Painting
606	Deck Covering
607	Hull Insulation
608	Storerooms, Stowages & Lockers
609	Equipment for Utility Spaces
610	Equipment for Workshops, Labs & Test Areas
611	Equipment for Galley, Pantry, Scullery & Commissary Outfit
612	Furnishings for Living Spaces
613	Furnishings for Offices, Control Centers & Machinery Spaces

Sub Group	Description
614	Furnishings for Medical, Dental Spaces
615	Radiation Shielding
650	Outfit & Furnishings, Repair Parts
651	Outfit & Furnishings, Operating Fluids
Armament--Group 7	
700	Guns, Gun Mounts, Ammo Handling & Storage (BSCI 700, 701, 702)
703	Special Weapons Handling & Stowage
704	Rocket & Missile Launching, Handling & Stowage Devices (BSCI 704, 705, 706, 707)
708	Torpedo Tubes, Torpedo Handling & Stowage
710	Mine Handling Systems & Stowage
711	Small arms & Pyrotechnic Stowage
712	Air Launched Weapons Handling & Stowage (BSCI 712, 713)
720	Cargo Munitions Handling & Stowage
750	Armament Repair Parts
751	Armament Operating Fluids
Loads--Group 8	
800	Ships Officers, Crew & Effects
801	Troops & Effects
802	Passengers & Effects
803	Ships Ammo
804	Aviation Ammo
805	Aircraft
806	Provisions and Personnel Stores
807	General Stores
808	Marines Stores
809	Aero Stores
810	Ordnance Stores Ship
811	Ordnance Stores AV
812	Potable Water
813	Reserve Feed Water
814	Lube Oil Ship
815	Lube Oil Aviation
816	Fuel Oil
817	Diesel Oil
818	Gasoline
819	JP-5
820	Miscellaneous Liquids

Sub Group	**Description**
821	Cargo
822	Ballast Water
825	Future Development Margin

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